VOL. 248 APRIL 1950 No. 4

American Journal of Science

Established in 1818 by Benjamin Silliman

EDITORS

CHESTER R. LONGWELL - JOHN RODGERS

ASSOCIATE EDITORS

REGINALD A. DALY . . . . . A. F. BUDDINGTON
CAMBRIDGE, MASS. PRINCETON, N. J.

ADOLPH KNOPF . . . . . RICHARD FLINT
CARL O. DUNBAR . . . . . HAROLD G. CASSIDY
HENRY MARGENAU . . . G. EVELYN HUTCHINSON
NEW HAVEN, CONN.

LEASON H. ADAMS . . . . WILMOT H. BRADLEY
WASHINGTON, D. C.

WILLIAM H. TWENHOFEL . . HOWELL WILLIAMS
ORLANDO, FLORIDA BERKELEY, CALIF.

FREDERICK J. ALCOCK . . . . CECIL E. TILLEY
OTTAWA, CANADA CAMBRIDGE, ENGLAND

GEORGE GAYLORD SIMPSON
NEW YORK, N. Y.

STERLING TOWER
NEW HAVEN, CONNECTICUT

Published monthly. Eight dollars a year. Seventy-five cents a copy.
Foreign, eight dollars sixty-cents. Canada, eight dollars thirty-five cents.

WILEY

New Books and a New Edition

BOTANY

An Introduction to Plant Science. By W. W. ROBBINS and T. E. WEIER, both at *University of California* . . . . Covers traditional subject matter with emphasis on more recent discoveries. Modern conception of life cycle including fertilization and meiosis, recent developments in plant anatomy, photosynthesis, respiration, structure of bacteria, water relations, genetics and chromosome structure are all thoroughly treated. Nearly 500 diagrams clarify important points . . . . *Ready in April. Approx.* 418 *pages.* 490 *illus. Prob.* $5.00.

ECONOMIC MINERAL DEPOSITS

By ALAN M. BATEMAN, *Yale University* . . . . A comprehensive account of mineral deposits, their occurrence and form. The interpretation of mineral deposits is stressed, and practical conclusions for ore finding are included. Post-war information added includes material on uranium. Bibliography expanded . . . . *Second Edition. Ready in April. Approx.* 918 *pages. Illus. Prob.* $9.50.

SELECTED INVERTEBRATE TYPES

Edited by FRANK A. BROWN, JR., *Northwestern University* . . . . An informative college level laboratory manual on the anatomy and physiology of subject matter. Covers approximately 100 commonly used American species, including the most widely studied fresh water forms. The types are organized on a classificatory basis. Each section includes selected bibliography . . . . 1950. 597 *pages.* 235 *illus.* $6.00.

EARTH WAVES

By L. DON LEET, *Harvard University* . . . . This is a concise summary of present knowledge about earth waves—fundamental facts and recent discoveries in the field. Discussion of their use in prospecting, studying hurricanes, mapping earth structures, etc. Data on two new wave types, interpretation of refraction profiles and microseisms—published for the first time. A HARVARD MONOGRAPH IN APPLIED SCIENCE . . . . 1950. 122 *pages. Illus.* $3.00.

ATLAS of DRAWINGS for CHORDATE ANATOMY

By SAMUEL EDDY, *University of Minnesota* . . . . A time-saving workbook for laboratory courses—in the form of unlabeled drawings made from original dissections, showing animal structures of common types, representing major classes of the CHORDATES in comparative arrangement by systems. Designed for full year course . . . . 1949. 150 *pages. Illus.* $3.50.

Send for copies on approval.

JOHN WILEY & SONS, Inc.

440 FOURTH AVENUE **NEW YORK 16, N. Y.**

American Journal of Science
APRIL 1950

THE JADEITE PROBLEM

PART I

HATTEN S. YODER, JR.

ABSTRACT. The literature is reviewed and new data on the jadeite problem are presented which redefine the probable stability range of jadeite. The mineral is known to occur in only three places: in Burma, as small masses in serpentine with albite or nepheline, or both; in Japan, also as small masses in serpentine with albite and quartz; and in Central America, but here no specimens have been found *in situ*. The interest in jadeite is due mainly to the theory that it is a high-pressure mineral. If a reaction is known to be possible on other grounds, it will proceed under pressure in the direction of smaller volumes. However, the mere fact that the supposed products are of smaller volume than the reactants is not sufficient basis for inferring that the reaction will take place. All attempts to synthesize jadeite, even at pressures up to 4000 atmospheres, have been unsuccessful.

Although no direct structure determination appears to have been made, the common assumption that jadeite has a structure similar to diopside is justified by an indirect method. It is suggested that the co-ordination of sodium is probably less than normally assigned and that the "excess" aluminum occupies silicon positions.

The temperature of formation is believed to be less than 800°C. since the mineral melts metastably at a temperature at least as low as 800°C.; it occurs with low temperature albite (<700°C.); it occurs in a reaction zone against serpentine (<500°C.); its chemical equivalents, nepheline + albite, appear to be stable in the presence of water down to 600° and 3000 atmospheres; and its glass fails to crystallize dry below 800°.

A new analysis of jadeite and data on the diopside—jadeite and acmite—jadeite joins are given. The jadeite problem is considered to be distinct from the eclogite problem.

INTRODUCTION

THE interest in jadeite, $NaAl(SiO_3)_2$, has arisen from a theory that it forms only under conditions of high pressure. At present jadeite stands as an example of a "high-pressure mineral" along with diamond and possibly the pyrope-almandine garnet. This view has been reached mainly from considerations of the eclogite problem since only one *in situ* deposit of jadeite has been studied in detail. The conditions of formation of the mineral jadeite have been considered analogous

to those of the rock eclogite even though the so-called jadeite molecule makes up only a small part, or even may be absent, in the eclogite pyroxene. These views on its formation are so firmly held that they are cited as evidence in the solution of earth structure problems. The purpose of this paper is to present new data which redefine the probable stability range of jadeite.

CHEMISTRY OF JADEITE

In 1863 Damour assigned the name jadeite to a mineral having the composition $NaAl(SiO_3)_2$. Since then it has been suggested that jadeite may constitute an important part of pyroxenes whose composition can be represented in terms of the end members acmite, hedenbergite, and diopside. These complex pyroxenes have been called omphacite, soda-augite, mayaite, chloromelanite, chromojadeite, lime-jade, fassaite, and others. The analyses of some 65 of these soda-alumina-bearing pyroxenes have been collected and their soda and alumina contents plotted in figure 1.

On first inspection one would conclude from the figure that there are essentially two different groups of jadeitic pyroxenes. However many of the analyses were made from artifacts such as jewelry and axe heads of both modern and ancient

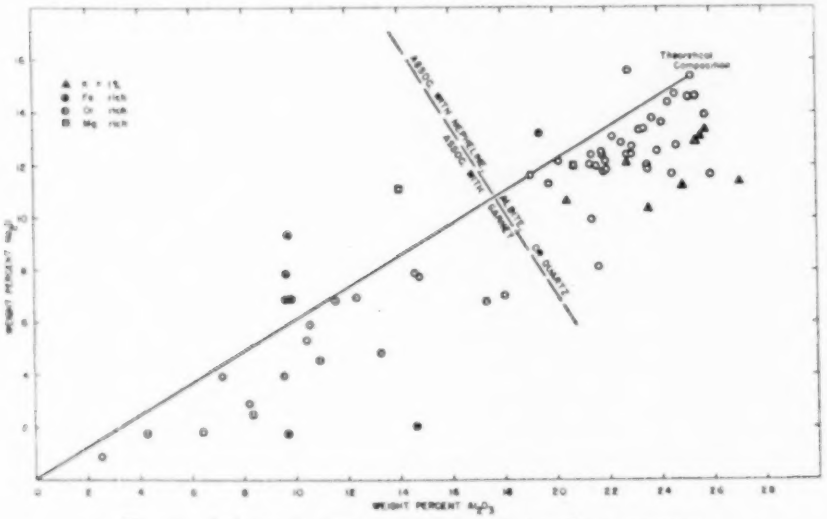


Fig. 1. Soda and alumina contents of complex pyroxenes.

civilizations. In addition many of the carved specimens may have been taken from the same boulder or fragment and therefore their analyses give undue weight in any statistical consideration. Others were made from impure pyroxenes separated from eclogites and other rocks. Most of the analyses were made around the year 1900. In spite of these shortcomings, the analyses show several interesting points. The group which most nearly approximates the ideal formula for jadeite are considered to be from only three distinct areas.

(1) Those specimens labeled as being obtained from Burma, China (Yunnan province), and Tibet are all believed to come from deposits in Burma. Many of the specimens from the Burmese localities were derived from a conglomerate, but for the past sixty years some have also been obtained from nearby *in situ* deposits. In order to avoid payment of royalties, according to Bleeck (1908), the Burmese jadeite had been smuggled across the borders to Yunnan, China, and to Tibet.

A locality was thought to exist near Karakash, Chinese Turkestan. This was also known as the Khotan or Kuen-Lung Mountain deposit. Musketov and Arzuni (Blagdanowitsch, 1892) believed that nephrite had been formed here at the expense of chloromelanite, but that no pyroxene was actually identified. In a personal communication, W. F. Foshag said no jadeite had been found in the specimens he had received from that locality.

Those analyses which contain a high percentage of potassium are said to come from China. It is not known whether these might not be from a particular boulder, containing orthoclase, which had been transported from Burma to China by man.

(2) A second locality, near the village of Kotaki, Niigata Prefecture, Japan, has been described in Japanese. Specimens have been received by the National Museum.

(3) A third locality is thought to exist in Central America (Oaxaca or Guerrero, Mexico, and Guatemala) where another conglomerate (Washington, 1922a) has apparently yielded boulders of jadeite. Neither the source of these boulders nor the original outcrop of jadeite has been found.

Another locality may exist in Switzerland, but it is more likely that the axes found were made from a single boulder erratic such as has been found in South Serbia (Tucan, 1929).

Without considering the archeological aspects of these localities, it can be said that there are essentially three deposits of a mineral which closely approximates the composition of jadeite. The important observation concerning these sources is that in each case jadeite is associated with nepheline or albite, or both. The remainder of the analyses are dominantly of pyroxenes taken from eclogites of various localities. In those cases the pyroxene is associated with a garnet. In figure 1 the straight line represents the ratio of soda to alumina calculated for the ideal jadeite. As has been pointed out by several writers, the alumina is generally in excess of that required for the ideal jadeite formula. This excess and the role of iron and magnesium will be interpreted on a structural basis in the following section.

STRUCTURAL ASPECTS OF JADEITE

In 1925 Wyckoff, Merwin, and Washington compared the spacings obtained from a diffraction pattern of jadeite with the corresponding lines of diopside. They found that the average spacings were some 3 per cent less than those for diopside. It was stated that jadeite has a similar pattern and therefore a closely related structure to diopside. The patterns were made on an unanalyzed sample from Middle America; the spacings were not published.

Of the monoclinic pyroxenes diopside is the only one for which a complete x-ray structure analysis has been made (Warren and Bragg, 1929). Warren and Biscoe (1931) state that from a comparison of augite, acmite, and spodumene, they "may reasonably conclude that diopside, hedenbergite, augite, clinoenstatite, acmite, jadeite, and spodumene are all monoclinic pyroxenes with diopside as the type structure." With the possible exception of spodumene they agree with the work done in 1925. It is to be noted that no diffraction patterns were made on a specimen of jadeite (this was confirmed in a personal conversation with Dr. Warren in 1948).

In 1932 Merritt published the lines for an unanalyzed specimen from "China." He said the pattern for jadeite is " . . . quite distinct from either diopside or acmite, although there is apparently a certain similarity."

In an attempt to resolve this difference of opinion, powder diffraction patterns were made of jadeite, acmite, diopside, and clinoenstatite on a recording x-ray spectrometer. The Geiger-

counter x-ray spectrometer (Norelco) was calibrated with a quartz standard using the following values:

hkl	2θ	d
100	20.876	4.2549 A.
101	26.664	3.3432
112	50.186	1.8177

The given d spacings are based on a weighted $CuK\alpha = (2K\alpha_1 + K\alpha_2)/3 = 1.5418$A. Dr. L. H. Adams has shown that the Norelco instrument will consistently reproduce angles measureable to 0.02°. A nickel filter was used.

The jadeite from Burma (USNM #94829) has been analyzed with extreme care by E. G. Zies:

SiO_2	59.51	Na_2O	14.37
TiO_2	0.01	K_2O	0.02
Al_2O_3	24.31	FeO	0.03
Fe_2O_3	0.35	MnO	0.01
Cr_2O_3	0.01	P_2O_5	0.00
CaO	0.77	H_2O+	0.06
MgO	0.58		
		Total	100.03

This material had been examined optically by H. E. Merwin and found to be free of mineral inclusions. Dr. O. F. Tuttle was of the opinion that he had observed a sufficient number of liquid inclusions in a single thin section to account for the 0.06 per cent H_2O+ in the analysis.

The jadeite from Japan (USNM #105860) contained a large number of liquid inclusions in addition to tremolite and albite. Most of the included material in another piece of the same specimen was removed after grinding by centrifuging in Clerici solutions prepared by K. Neuvonen. The removed material after x-ray examination was identified as analcite by comparison with known patterns. No analcite was seen in the thin section prepared.

The acmite was from Quincy, Massachusetts, and has been described by Palache and Warren (1911). The material was taken from the same sample analyzed by Washington (Washington and Merwin, 1927).

The natural diopside was collected by F. E. Wright at Ham Island, Alaska, and its analysis is given by Allen and White (1909). The synthetic diopside was prepared by J. F. Schairer.

The clinoenstatite was taken from the material prepared by Bowen and Andersen (1914). The spacings smaller than 1.731 did not agree with those of Clark (1946).

A visual similarity was noted among clinoenstatite, acmite, and jadeite in both spacings and intensities. The intensities of diopside appeared to be unique among the group. This could have been anticipated from the much larger scattering power of the calcium with respect to the other atoms (except Fe). In order to compare jadeite more closely with diopside, whose structure is known, it was necessary to find a method of indexing its planes. Not having accurate unit cell data, it was assumed that the "c" dimension is approximately the same for all pyroxenes. Using the morphologically determined crystallographic ratios and beta angle of Penfield (Kunz, 1900), a reasonable unit cell size was calculated:

$$\beta = 72° \ 44.5' \qquad 1.103 : 1 : 0.613$$
$$a = 9.45 \text{ A.}$$
$$b = 8.57$$
$$c = 5.25$$

An accurate check may be made on the dimensions of this unit cell. The volume of the cell, using the above values, calculated by the formula $V = abc \sin \beta$, is 406 A^3. The volume may also be determined using the formula $V = Mn/N_o\delta$ where:

M = molecular weight = 202.09
n = number of molecules in unit cell = 4
N_o = Avogadro's number = $6.023 \pm 0.001 \times 10^{23}$
δ = density = 3.328 at 30.9°C. (Adams and Gibson, 1929).

This is equal to 403.28 A^3. It is concluded that the calculated unit cell dimensions are reasonable. The spacings for this assumed unit cell were calculated for most of the hkl's permitted in the space group to which diopside is assigned, C_{2h}^6, by the formula

$$d = \left(\frac{\frac{h^2}{a^2} + \frac{l^2}{c^2} - \frac{2hl \cos \beta}{ac}}{\sin^2 \beta} + \frac{k^2}{b^2} \right)^{-\frac{1}{2}}$$

The calculated d's are listed in table 1 for comparison with those of the diopside from deKalb, New York. Those spacings for the deKalb diopside for which intensities are indicated were determined by Warren and Bragg (1929), the others were calculated. The pattern of the Burmese jadeite recorded

on film was taken and measured independently by A. J. Frueh for the purpose of comparing the two methods. It is seen that all the lines from the powder patterns can be assigned an index within the space group criteria. It appears as though acmite, jadeite, and clinoenstatite are pyroxenes having diopside as the type structure.

This specific problem can be approached in another way. If jadeite has the type pyroxene structure of diopside (XYZ_2O_6), a stable structure should result when Na and Al are substituted in the X and Y positions respectively. In diopside there are three distinct oxygen positions. The Pauling bond situation for these oxygens may be diagrammatically represented as in figure 2a. Here each bond is assigned a strength dependent on the charge and co-ordination of the atom in accordance with the Electrostatic Valence Rule (Pauling, 1929). It is seen that such an arrangement does not lead to a stable structure. Following the suggestion of Bragg (1937, p. 187), if two of the bonds co-ordinating the calcium atom to oxygens are assumed inactive, a stable structure results (figure 2b). In effect the bonding becomes that of clinoenstatite (YYZ_2O_6). To obtain the jadeite structure it should only be necessary to substitute Na in the calcium positions and Al in the Mg positions. Again assuming a six-fold co-ordination for the calcium position (as in spodumene and clinoenstatite) the bonding picture becomes that of figure 2c. This is not unreasonable for dominantly ionic structures, but a further improvement may be made. Buerger has made the suggestion that the co-ordination of the alkalies is, in general, too high. He postulated that sodium may have a co-ordination as low as four. Sodium has a co-ordination of four in Na_2O and also in the nepheline structure. For jadeite the bonding picture then becomes that of figure 2d. Such an analysis is limited by the fact that the bonds are not entirely ionic and that only the nearest neighbors are considered. However, it may be concluded that the assumed structure for jadeite is reasonable from the standpoint of bonding.

It is obvious that a more general picture must be considered than the simple substitution of sodium and aluminum in the proper positions. Warren and Biscoe (1931) have expressed the general formula for the pyroxenes as follows:

$$X_mY_{2-m}(Si,Al)_2(O,OH,F)_6,$$

TABLE 1

X-Ray Powder Diffraction Measurements of Diopside and Jadeite

C_{2h}^6	Diopside deKalb, N.Y.		Diopside Synthetic		Diopside Ham Is. Alaska		Jadeite Calculated	Jadeite Burma-film		Jadeite Burma-spec.		Jadeite Japan-spec.	
hkl	d(Å)	I	d(Å)	I	d(Å)	I	d(Å)	d(Å)	I	d(Å)	I	d(Å)	I
110	6.45	0	N.O.		N.O.		6.21	6.19	4	6.18	1	6.18	1
200	4.68	0	N.O.		N.O.		4.52	N.O.		4.49	½	4.52	½
020	4.45	1	4.40	1	4.44	½	4.28	4.29	8	4.27	3	4.29	3
?	...	..	...	..	...	..	...	...	..	3.89	½	3.89	½
021	3.34	3	3.33	1	3.33	½	3.26	3.25	5	3.25	1	3.25	1
220	3.23	3	3.22	4	3.23	8	3.11	3.11	5	3.10	3	3.11	2
221	2.99	..	2.98	10	2.98	10	2.93	2.92	10	2.92	8	2.93	1
310	2.96	6	2.94	3	2.94	7	2.84	2.82	10	2.83	10	2.84	6
311	2.89	..	2.88	4	2.89	1	2.84						
130	2.84	½	2.79	½	2.82	½	2.73	N.O.		2.68	½	N.O.	
202	2.54	3	2.56	3	2.56	1	2.53						
002	2.53	10					2.51	2.50	8	2.49	2	2.50	3
131	2.53		2.52	8	2.53	4	2.49						
112	2.52						2.52						
221	2.51						2.43	2.42	8	2.42	9	2.43	2
131	2.41	..	2.39	½	N.O.		2.31	N.O.		2.31	½	2.31	½
400	2.33	1	2.29	2	2.29	1	2.25	2.24	6	2.24	½	N.O.	
040	2.22	0	2.21	1	N.O.		2.18	N.O.		N.O.		N.O.	
312	2.23				N.O.		2.21	2.19	6	2.20	2	2.21	½
022	2.19	5	2.19	1	2.18	½	2.16	N.O.		2.15	1	2.16	1
330	2.144	4	2.146	2	2.146	2	2.071	2.069	7	2.067	3	2.075	2
331	2.129	..	2.121	5	2.124	2	2.069	...	..	....	..	....	..
421	2.103	..	2.101	1	2.101	3	2.049	N.O.		2.043	1	2.046	1
420	2.078	2	N.O.		N.O.		1.999	N.O.		1.991	½	1.996	½
041	2.033	6	2.034	3	2.034	1	1.967	1.971	6	1.966	1	1.970	1

TABLE 1 (Continued)

X-Ray Powder Diffraction Measurements of Diopside and Jadeite

C_{2h}^{6} Diopside deKalb, N.Y.			Diopside Synthetic		Diopside Ham Is. Alaska		Jadeite Calculated	Jadeite Burma-film		Jadeite Burma-spec.		Jadeite Japan-spec.	
hkl	d(Å)	I	d(Å)	I	d(Å)	I	d(Å)	d(Å)	I	d(Å)	I	d(Å)	I
240	2.017	1	N.O.		N.O.		1.934	N.O.		N.O.		N.O.	
202	2.012	6	N.O.		N.O.		1.959	N.O.		N.O.		N.O.	
402	2.010	6	2.008	2	2.002	3	2.002	N.O.		N.O.		N.O.	
241	1.948	..	1.954	1	1.959	½	1.888	1.892	3	1.887	1	1.893	½
511	1.892	..	N.O.		N.O.		1.842	N.O.		1.835	½	1.841	½
?	....	..	1.853	½	N.O.		1.768	....	..	....	..	....	..
510	1.836	4	N.O.		N.O.		1.810	1.761	5	1.760	2	1.763	1
422	1.833	..	1.828	1	1.830	½	1.683	N.O.		1.807	½	1.810	½
332	1.815	..	1.806	½	1.809	½	1.707	1.687	5	1.683	2	1.688	1
42$\bar{1}$	1.773	..	N.O.		N.O.		....	N.O.		N.O.		N.O.	
150	1.752	6	1.750	2	1.748	4	1.683	See 332		See 332		See 332	
312	1.711	..	1.720	½	1.680	½	1.662	N.O.		N.O.		N.O.	
042	1.668	5	1.670	1	1.668	½	1.629	1.623	2	1.623	½	1.626	1
313	1.657	..	1.656	1	1.655	½	1.657	1.656	2	1.652	½	1.655	½
441	1.627	..	N.O.		N.O.		1.578	1.577	6	1.570	4	1.574	2
223	1.623	..	1.620	3	1.622	2	1.616	1.613	2	1.608	½	1.610	1
440	1.612	4	N.O.		1.612	2	1.553	1.553	5	1.551	1	1.554	1
530	1.590	3	N.O.		N.O.		1.526	N.O.		1.523	½	1.526	½
023	1.584	½	N.O.		N.O.		1.576	See 441		See 441		See 441	
600	1.558	7	1.559	½	1.560	½	1.504	1.508	3	1.498	1	1.503	1
350	1.552	5	1.548	1	1.548	½	1.488	1.484	3	1.488	1	1.483	1
602	1.525	6	1.524	1	1.520	1	1.499	See 600		See 600		....	..

$I = I_{(hkl)}/I_{10}$

N.O. = not observed.

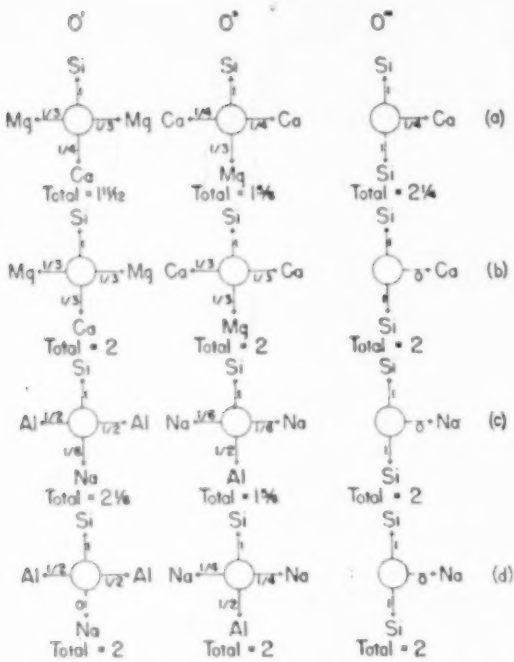


Fig. 2. Co-ordination of oxygens in pyroxene structures.

where X may be Ca, Na, K, Mn, and where Y may be Mg, Fe, Al, Ti, Mn, Li, and m tends to be either 1.0 or 0. Although there is insufficient data to define the limits, if any, of these substitutions, the following aluminous pyroxenes have been recognized:

Jadeite	$(Na,Ca)(Al,Mg)(Si,Al)_2O_6$
Omphacite	$(Ca,Na)(Mg,Fe^{+2},Al)(Si,Al)_2O_6$
Chloromelanite	$(Ca,Na)(Mg,Fe^{+3},Al)(Si,Al)_2O_6$
Augite	$Ca_x(Mg,Fe^{+2},Fe^{+3})(Si,Al)_2O_6$
Fassaite	$Ca(Mg,Al)(Si,Al)_2O_6$

The groups as defined above represent only one opinion; the terminology is greatly in need of revision. The role of the "excess" alumina is that of a proxy for silica; an aluminum in a silicon position has a co-ordination of four. Warren and Biscoe further point out that as much as one-fourth of the silicon positions may be occupied by aluminum. In such a case the local bonding picture is satisfied if the atom in the calcium

position is allowed to change co-ordination as the situation dictates. Osborn (1942) has demonstrated that diopside can take up aluminum in its structure. It would be of great interest to learn the precise role of aluminum in such structures as fassaite. It is conceivable that the pyroxene structure may be controlled by activation or inactivation of some of the alkali bonds, or by the change in co-ordination of aluminum, or by both. How these changes may be brought about by changes in temperature or pressure are discussed in the following paragraphs.

The co-ordination of calcium is thought to be a function of temperature. According to Brandenberger (1936) and others, the calcium in Ca_2SiO_4 should surround itself with a smaller number of oxygens in the higher temperature forms. Bredig (1945) believes the higher temperature form to have its calcium in the higher co-ordination. The first view is based on the Goldschmidt Rule (1926) that at high temperatures that crystal structure is stable which could be obtained by substituting a cation having a greater electrostatic influence. The latter view is based on the argument that the weaker bond (Ca-O) becomes weaker, that is, the bond distance increases making greater co-ordination possible, before the stronger bond (Si-O) is affected. One would expect that the more loosely packed structures, for example, where the atom has the lower co-ordination, would exist at the higher temperatures. Buerger (1948, p. 115) also believes that there is a tendency toward lower co-ordinations at higher temperatures. He says that "Atoms in lower coordination are freer to wander over larger volumes, and thus have larger entropies." There is some reason, therefore, to believe that the co-ordination of the alkalies is a function of temperature.

Jadeite has most of its aluminum in the Y position (CN = 6) rather than in the Z (Si,Al) position (CN = 4). From geometrical considerations alone, it can be said that aluminum in six-fold co-ordination is in closer packing than when in four-fold co-ordination. In that packing is dependent on the ratio of the atomic sizes, it is therefore dependent on composition. This is shown strikingly by substituting the light weight NaAl combination in place of the heavier CaMg in the pyroxene structure; the density increases. In other words, if the composition is fixed, there exist limitations to the type of packing.

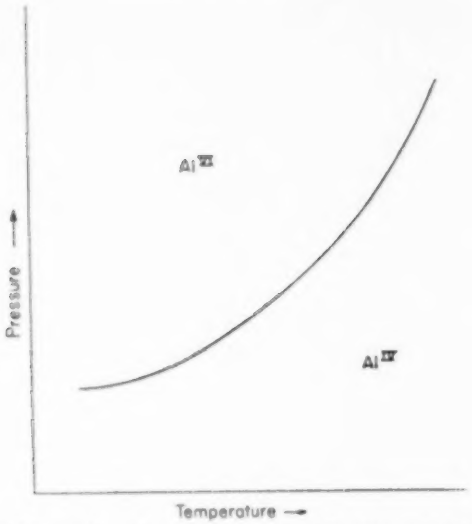


Fig. 3. Stable regions for different co-ordination of aluminum (after Thompson, 1947).

From a study of the chemical analyses, it appears that calcium throws aluminum into four-fold co-ordination and sodium throws it into six-fold co-ordination in the pyroxene structure. Other factors (*i.e.*, structural type) should be considered since in grossularite, for example, the aluminum is in six-fold co-ordination in the presence of calcium.

Wickman (1943) and Thompson (1947) consider the co-ordination of aluminum to be a function of pressure and temperature as shown in figure 3. (This shift in co-ordination is similar to the shift in co-ordination thought to occur in carbon as in figure 4.) Wickman, however, qualifies his statement by saying that in the presence of the strongly polarizing OH group the aluminum may also have six-fold co-ordination. Wang (1939) suggested that the co-ordination of aluminum was controlled by the amount of volatiles present. Of the soda-alumina-silicate minerals which have all their aluminum in six-fold co-ordination (glaucophane, tourmaline, and sodium montmorillonite, for example), only jadeite is considered to be anhydrous.

Much stress has recently been laid on the co-ordination of aluminum as a function of pressure. The concept of space conservation under high pressure can be traced back to the

Volume Law of Lepsius (1893, p. 191). The fact remains, however, that logically one cannot step directly from a minimum volume product to the agent of high pressure without intermediate considerations, *i.e.*, composition and temperature. These often overlooked considerations will be stated more precisely later in thermodynamic terms. Where the association is jadeite with albite or nepheline, or both, the aluminum is in both IV and VI. When the association is jadeite and garnet, the aluminum is dominantly VI. These two different types of association will be fully described in the following sections.

ASSOCIATION WITH NEPHELINE OR ALBITE, OR BOTH

Only one deposit, Upper Burma, has been studied where jadeite occurs *in situ* with albite or nepheline, or both. Noetling (1892) first described the deposits at Tawmaw (or Tammaw), Burma, as a vein in a black rock. Later (1893) he said the jadeite was intimately associated with an eruptive rock closely resembling serpentine. In 1896 Noetling finally concluded that the jadeite was either a separate intrusion into the serpentine or a cooling modification of the serpentine. The rocks collected by Noetling were described in detail by Bauer (1895). Bauer

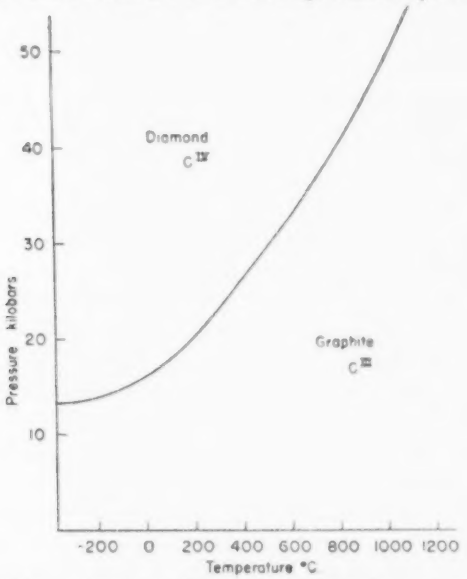


Fig. 4. Stable regions for different co-ordination of carbon (after Goranson, 1940).

thought that the Burma jadeite could not be considered an eruptive rock since jadeite had not been found in established eruptive rocks. Of particular interest is a fragment of a boulder, said to have come from Tibet, which Bauer (1896) described. In it were found jadeite, nepheline, and albite—locally one more abundant than the others. In one preparation needles of jadeite were completely enclosed by the nepheline; only small amounts of basic plagioclase were present. Bauer (1897) later said that the "Tibet" material occurred in a chlorite schist. In 1906 Pirsson and Iddings (Bishop, 1906, p. 162) described several specimens from Burma which contained either albite or nepheline. They considered the jadeite to be a constituent of a metamorphosed igneous rock (phonolite) and cited as evidence the cataclastic structure, the lack of (OH) bearing minerals, and the general absence in known igneous rocks. In the same year Bauer (1906) noted further in a specimen from Burma that jadeite occurred with plagioclase and contained needles of orthoclase.

In 1907 the deposit was again studied by Bleeck (1907, 1908) who described it as a broad dike in serpentine. Judging from the extent of the mines and quarries, the deposit was roughly 600 feet wide and 1500 feet long. A section through the dike is represented in figure 5. (The zone between the jadeite and serpentine was described by Noetling as "clayey soft serpentine." Later Chhibber (1934) described a similar zone as consisting of a crushed mixture of serpentine and jade-

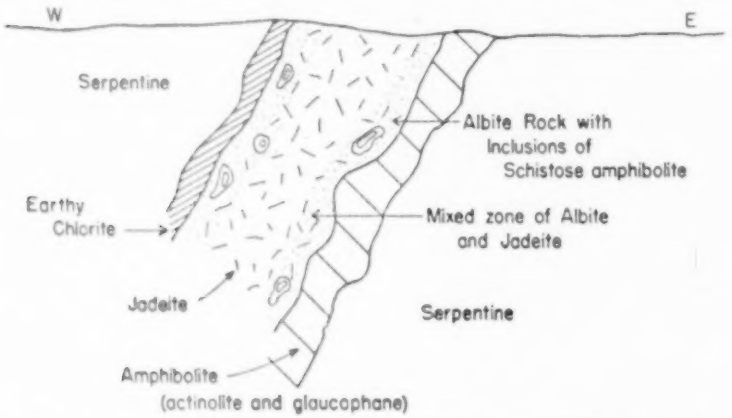


Fig. 5. Cross section of Tawmaw, Burma, dike (after Bleeck, 1907).

ite or amphibole in an irresolvable base.) Bleeck emphasizes the fact that albite is an important constituent of the dike. He says the intrusive nature of the dike is proved by the inclusions of the country rock and the veinlets of albite-jadeite extending into the country rock. Bleeck is of the opinion that the dike originally solidified as a nepheline-albite rock which later, under metamorphism at a very high pressure, was transformed into an albite-jadeite rock according to the equation:

$$\text{nepheline} + \text{albite} = 2 \text{ jadeite}.$$

(The formation of jadeite by this reaction results in a 21.3% reduction in volume.) This follows the suggestion of Rosenbusch (1898, p. 508). The minerals developed in the wall rock are considered to be produced as a result of a reaction between the serpentine and the dike. This metamorphism was caused by a later intrusion of granite into the area.

Lacroix (1930) from his studies of Burmese specimens from museums and Chinese lapidaries came to the conclusion that the dike entered as a highly aluminous and sodic magma containing an excess of silica, stoping and metamorphosing its walls. Through desilication of the magma by the peridotite, the amphibolite zone was formed. The intrusion took place under high pressure, according to Lacroix, which permitted the production of minerals having the smallest volume, *i.e.*, jadeite.

A third field study was made of the Burma deposit by Chhibber (1934). His detailed examination of the mining operations and of many recently discovered outcrops in the jungle resulted in a picture somewhat different from that of Bleeck. The outcrops suggested to him that there are four dikes or sills intrusive into the peridotites and serpentines. The most recent workings in the Tawmaw dike (originally described by Bleeck) indicate that the jadeite occurs as large lenses from five to seven feet thick in the albite of the foot wall side. These lenses are separated by amphibolite, albitite, or an albite breccia. Chhibber believes the parent of the dike was a soda-granite-aplite which was a normal differentiation product of the granite magma which had penetrated the area. He postulated high pressure operating during the consolidation of the rock as the controlling factor, but also suggested that composition might be important. He notes that nepheline syenite is usually accounted for by desilication of albite; the intermediate compound could have been formed by a limited

desilication of albite. In general Chhibber agrees with the conclusions of Lacroix.

The authors agree that the source materials for the formation of jadeite are of igneous origin, and that pressure was the controlling factor. They disagree as to whether pressure was active during (piezocrystallization) or after (dynamometamorphism) the consolidation of the rock. Bleeck says that only the metamorphic reaction $Ne + Ab = 2Jd$ can account for the associations of Jd + Ne and Jd + Ab. Lacroix points to densities as favoring crystallization under high pressure. These explanations must be regarded as speculations and not proofs for such processes.

It is true the association of jadeite with albite or nepheline, or both, has been found in only three localities; but it is to be noted that there are nepheline-albite rocks which do not contain a pyroxene, and, on the other hand, there are many such rocks which contain an acmitic pyroxene. The presence of iron also permits a mineralogy such as nepheline, sodic-pyroxene, and a garnet, as in the ijolites. Such an association may be the link between the nepheline-albite-jadeite rock and the garnet-jadeitic pyroxene rock.

ASSOCIATION WITH ALBITE AND QUARTZ

Very similar to the Burmese deposit is the jadeite deposit of Kotaki Village, Kubiki County, Niigata Prefecture, Japan (36°55′N, 137°50′E). Information on the deposit has been obtained mainly through the kindness of S. K. Neuschel, who, at the request of the writer, had a special report prepared by Helen L. Foster (1949). Information for the report and map was obtained from an interview with Schuichi Iwao, geologist for the Geological Survey of Japan, who has made detailed studies in the area. Two articles, published in Japanese, by K. Omori (1939), and by Y. Kawano (1939) have been translated in part by Dr. Joseph G. Hoshioka for the writer.

Jadeite was first discovered in 1938 in a block in the bed of Kotaki River. Kawano (1939) reported that a dozen and a half or so boulders up to several meters in diameter within a distance of 150 meters along the river were later found. He describes the jadeite deposit as being in a serpentine body, triangular in shape, bounded on the northeast by a fault against limestone, on the west by a conglomerate, and on the

south by sandstone and shale. The contact relationships were mostly obscured by talus and the actual exposures of the jadeite in place were not observable according to Kawano. Essentially the same relations were indicated by Kiyohiko Ishii who surveyed the region in 1932 (see Shiroumadake Sheet No. 136, Imperial Geological Survey of Japan). The mineral was described as occurring with actinolite and wollastonite and for this reason was thought to have been a product of contact metamorphism of the limestone. Omori (1939) also listed albite and tremolite as inclusions in the jadeite. It was not mentioned whether nepheline or quartz were present. Omori gave the indices of both the white and green jadeite as:

$a = 1.658$ $\beta = 1.663$ $\gamma = 1.673$ $c \wedge z = 38°$

Two chemical analyses have been made on the Japanese jadeite by Kawano:

	Theoretical	Green Jadeite	White Jadeite
SiO_2	59.44	58.02	58.35
Al_2O_3	25.22	22.96	23.90
Fe_2O_3		0.77	0.66
FeO		0.18	0.08
MgO		1.70	0.78
CaO		1.58	0.98
Na_2O	15.34	12.38	12.53
K_2O		0.16	0.12
H_2O+		0.87	1.24
H_2O-		0.61	0.67
TiO_2		0.04	0.04
MnO		0.01	0.00
Total	100.00	99.28	99.37

A thin section of the white jadeite with patches of green (USNM #105652) contained many inclusions both mineral and liquid. One vein cutting the section, about 0.1 mm. wide, contained a fibrous mineral of high index (approximately 1.60) and moderate birefringence. It is tentatively identified as tremolite. Being the dominant included mineral, the high H_2O+ in the analyzed jadeite could be accounted for by its presence in addition to the many liquid inclusions. It is to be recalled that considerable analcite was found in one sample. The details of the occurrence of the jadeite are quoted from the Foster report:

"The jadeite occurs with albitite and quartz. The so-called albitite is said to have a composition more like that of oligoclase

than of albite. Minor constituents of the rock include grossularite, actinolite, talc, muscovite, biotite, pyrogopite, vesuvianite, zoisite, and hydrous wollastonite [xonotlite?]. No nephelite is associated with the jadeite. There are numerous occurrences of albitite which have no jadeite.

"The jadeite and associated albitite are found in rock composed principally of serpentine. In a typical occurrence, a central mass of albitite is surrounded by a series of concentric zones of different mineral compositions. The composition of the zones, from the innermost which surrounds the albitite to the outermost is (1) white jadeite which contains patches of green jadeite, (2) green jadeite, (3) actinolite mixed with green jadeite, (4) actinolite, and (5) serpentine. The width of the zones which contain jadeite vary from one-fourth of an inch to about two inches."

Four outcrops of jadeite were indicated by Iwao on a U.S. Army base map, three of which do not lie in the serpentine body as outlined by Ishii. This discrepancy cannot be accounted for at this time.

The similarity to the Burmese occurrence is striking; the main exceptions being the presence of quartz and the variety of minor constituents. Quartz as a major constituent immediately raises a question since quartz, albite, and jadeite cannot coexist under equilibrium conditions. Fermor (1938) suggested the following equation for the formation of jadeite from albite: albite = jadeite + quartz. This may well represent the case. There is, however, a consistent decrease in silica content from the albite core to the surrounding serpentine.

Some Japanese geologists believe the jadeitic masses to have formed from the residuum of a Mesozoic magma. Others have suggested that they resulted from contact metamorphism of the Paleozoic limestone.

ECLOGITES

A second type of association is a jadeitic pyroxene with garnet in the rock eclogite. Eclogite occurs only as lenses, masses, bands, or schlieren of small size in rocks of basic or ultrabasic composition. The structure is massive and the texture is described as granular and sometimes cataclastic. This picture is not unlike that of the nepheline-albite association. The eclogite is a bi-mineralic rock consisting of pyroxene, garnet, and a small amount of accessories. The pyroxene, usually called omphacite, is dominantly diopsidic and carries

small amounts of soda (0 to 8 per cent, average 4 per cent for 18 specimens) and alumina. The garnet is of the almandine-pyrope series and may carry appreciable amounts of grossularite.

A review of the literature from 1822 when Haüy (p. 456) first defined an eclogite indicates that there are six principal schools of thought on the formation of eclogites:

I. Direct crystallization from a magma under high hydrostatic pressure.
II. High-grade metamorphism of igneous or sedimentary rocks.
III. Metasomatism of sedimentary or igneous rocks.
IV. Dynamic metamorphism of pre-existing rocks.
V. Hydrothermal contact metamorphism.
VI. Migmatization or diatectic metamorphism.

The first two schools believe in the necessity of high pressure and high temperature for the formation of eclogites, but differ in the origin of the material. Most field workers are of this general opinion. The following is a composite of arguments, independent of area, which have been used by these workers.

1. The density (or high degree of packing) of the characteristic minerals and the rock as a whole suggest that an eclogite would occupy less volume under pressure than a gabbro of corresponding composition. This has been illustrated to be in accordance with the Le Chatelier principle by the reaction: augitic pyroxene + plagioclase = omphacite + garnet.

2. The elastic properties of the rock suggest that it is to be found in the deeper portions of the earth where high hydrostatic pressures and high temperatures are known to exist.

3. The occurrence of "fragments" of eclogite in the pipes of South Africa and Australia have been interpreted by some as evidence of a deep-seated source. (These first three arguments have given rise to the postulate that an inner shell of the earth consists of eclogite.)

4. Several field workers have noted that certain retrograde reactions have occurred in the eclogite, such as the formation of a diopside-plagioclase-symplectite, intergrowths

of hornblende and plagioclase, and "feldspar uralites" from the pyroxene. These have been thought to be due to the release of pressure.

5. The associated tectonites and accompanying "high-pressure minerals" have been cited as evidence. Diamond, rutile, kyanite, and other accessories have been named.

6. It has been recorded that the eclogite minerals are not known in established igneous rocks formed under "normal" conditions.

7. The eclogite minerals have not been obtained in synthetic melts at one atmosphere pressure.

8. The small size of the occurrences has suggested to some that the bodies are the result of "intense local conditions."

9. The massive structure and granular texture were used as criteria for high temperature and high pressure crystallization.

10. The presence of a pyroxene as well as the lack of OH minerals was considered as evidence for high temperature conditions.

The above "criteria" for the formation of eclogite at high temperatures and high pressures have, of course, not stood without questioning. The following, in corresponding numerical order, are some of the objections raised against each of the above arguments.

1. High density in itself is not conclusive evidence that a reaction proceeded in a given direction under pressure; temperature and composition must also be considered. A simple analogy may be found in the statement that a reaction may go if the heat of reaction is negative; here the criterion should be free energy. In addition Wagner (1928) says that eclogites and basalts are not chemical equivalents.

2. Diabase and dunite have elastic properties similar to eclogite. Since diabase may also form near the surface, these properties cannot be conclusive evidence for deep-seated formation.

3. Many consider the "fragments" as "segregations" in a normal magma. Some agree that the "fragments" are carried up from depth, but that they are from an ancient metamorphosed complex whose conditions of formation can no longer be traced. Korjinsky (1937) concludes from the

absence of eclogite in the pre-Cambrian that it originated only at moderate depths.

4. The alleged retrograde reactions have also been interpreted as up-grade reactions; that is, the "inclusions" are relics. Even the "unmixed" pyroxenes of Hentschel (1937) may be due to normal magmatic processes.

5. The nearby tectonites have in some cases been shown to be produced after the formation of the eclogite. In some areas the associated rocks include limestone and shale. The existence of "high-pressure minerals" has yet to be proved.

6. The line between an igneous augite bearing a little soda and an omphacite is not very sharp. Garnets approaching the composition peculiar to eclogites have been found in skarn zones.

7. Not all the tricks of crystal growth have been employed in the attempted production of the eclogite minerals.

8. It has been suggested, in at least one area, that the small masses are remnants of much larger bodies. The large lenses, and dike-like bodies are border-line cases.

9. Massive structure and granular texture have also been assigned to low-grade metamorphism by some writers.

10. Diopside, the dominant portion of an eclogite pyroxene, is considered to be one of the first minerals to form in the metamorphism of a dolomitic limestone. Many writers have indicated that pyroxene is not a mineral critical to any particular set of conditions. Several field workers have reported the presence of zoisite, hornblende, mica, and others as primary minerals in the eclogite.

Almost every worker has based his conclusions on observations in only a single area, yet the freedom with which these interpretations have been applied to other areas is unusual, and only a few workers seem willing to concede that eclogites may form in more than one way. Although the division of thought into sharply delineated schools is a matter of convenience, the writer believes the following workers may be regarded as belonging to the first school of thought: Wang (1939), Eskola (Barth, Correns, Eskola, 1939, pp. 366-367), Harker (1932, pp. 307-308), Williams (1932, pp. 316-353), Waldmann (1929), Eskola (1921), Wagner (1914, p. 130), Ktenas (1907), Holland (1900, p. 245). In the second school of thought it is probably correct to list Davidson (1942),

Fermor (1938), Sahama (1935), Briere (1920), Stillwell (1918), du Toit (1908), Holway (1904). Another group of writers supporting the high-pressure, high-temperature schools are either non-commital as to the source of materials or suggest both sources as being possible: Turner (1948, p. 106), Baker (1945), Holmes (1936, p. 379), Eskola (1936), Alderman (1936), Ernst (1935), Tilley (1936), Adams and Gibson (1929), Eskola (1920), Fermor (1913), Clough (1910, pp. 32-35), Grubenmann (1910, p. 228), Hezner (1903), Rosenbusch (1898, p. 508).

The third principal school is of the opinion that eclogites are produced by the metasomatism of sedimentary or igneous rocks. Hentschel (1937) interpreted the eclogites of Gilsberg as a secondary product of a reaction between pneumatolytic or pegmatitic solutions and a peridotite. The resulting pyroxenite "unmixed" to give an eclogite pyroxene and garnet. Ghosh (1941) considered the charnockite series of Bastar State and Western Jeypore, in which eclogite occurs, as complexly metasomatized impure calcareous sediments rich in iron and magnesium. The chief criticism that has been raised against this last view is that it fails to explain "the world-wide association of basic charnockite and eclogite with anorthosite" (Davidson, 1942). Groves (1935) specifically states that no anorthosite is associated with the charnockite series in Uganda. Düll (1902) believes the eclogite of Munchberger to be the result of metasomatism of gabbro-norite by a "hot, acid bath" from a granite.

Another school of thought adheres to the view that the materials were subjected to the processes of dynamic metamorphism. Groves (1935) considers this to be the dominant factor while Eskola (Barth, Correns, Eskola, 1939, pp. 366-367), Backlund (1936), Kranck (1935), Waldmann (1929), Eskola (1921), and Hezner (1903) consider it only a contributing factor. Kranck, in particular, has presented a detailed account of the mechanics of the process. He cites the following evidence: rolled-out character of the bodies, rotational whorls in garnets, broken schistosity, mechanical mixing of eclogite minerals with surrounding gneiss, and the parallel arrangement of other minerals.

A fifth school is represented by those who consider the small bodies of eclogite to be a product of contact metamorphism:

Saranchina (1946), Switzer (1945), and Korjinsky (1941). Saranchina describes eclogite and amphibolite in which are preserved "armoured" fragments of gabbro-norite. The eclogite-amphibolite series is said to be produced where the gabbro is in contact with migmatite or pegmatitic veins. Switzer describes the formation of glaucophane schists through hydrothermal contact metamorphism by serpentine intrusives. In view of the intimate association in the field, he concludes that the eclogites were formed nearly contemporaneously and through the same genetic process. On the basis of chemical composition he believes the eclogite to be derived from basalt. Korjinsky considers talc deposits which were partly nephritic and possibly jadeitic to be formed where borders of "desilicified pegmatites" are in contact with hyperbasites and feldspar rocks. A deposit of similar mineralogy was reported near Mt. Vernon, Skagit County, Washington (Zodac, 1939), but the presence of jadeite has not been clearly established (personal communications from S. L. Glover, J. W. Melrose, and C. D. Campbell, 1948).

Still another school of thought believes that migmatization or diatectic metamorphism produces eclogites. This process is supported by Weiseneder (1937), Fiedler (1936), Weiseneder (1936 and 1932), Heritsch (1926), Fersman (1925), and in part by Backlund (1936) and Kranck (1935). Backlund relates the formation of eclogite to the passage of the migmatite front. He believes from his study in Greenland that the highest temperatures and extreme dynamic pressure give rise to the true eclogite. Fiedler explains the eclogite of Erzgebirge as a "particular metamorphic condition" in the amphibolite. Pre-existing materials have been affected by the "diatectic" process, *i.e.*, "pegmatitic solutions under high pegmatitic pressures." Weiseneder considers the eclogites to be the result of progressive thermal metamorphism under the influence of residual solutions from a local magma. He further notes that at the same time as this extreme metamorphism at depth there was a material exchange within the metamorphosed series.

It has been hoped from this rather lengthy review of the eclogite problem that some clue to the synthesis of jadeite could be found, but it seems as though eclogite has been considered to be formed by all known major geological processes pertaining to igneous and metamorphic rocks. It is the opinion

of the writer that the small amount of soda commonly found in the eclogite pyroxene does not justify the assignment of special extreme conditions for its formation. The well-established fact that specific bulk compositions may yield different mineralogies under slightly different environments does not require elaboration. The diopside-grossularite skarns should enjoy equal popularity under the criteria listed in the above arguments. In fact Weiseneder (1932) has used the term pseudoeclogite to describe such skarn deposits. Because of the apparently ubiquitous occurrence of the eclogite pyroxene and its low soda content, the eclogite problem is considered to be separate and distinct from the jadeite problem.

RELATION OF JADEITE TO ANALCITE

The formation of analcite, $NaAlSi_2O_6 \cdot H_2O$, is to be considered in that its composition is similar to jadeite. Being much different structurally, analcite should not be referred to as "hydrated jadeite." The secondary occurrence of analcite in vugs and cavities is well known. Its primary occurrence in basic rocks, although debated for many years (Scott, 1916), is apparently now accepted. Analcite has been observed as an alteration product of jadeite. The relation of analcite to nepheline and albite has been represented by the following: nepheline + albite + $2H_2O$ = 2 analcite. (Assuming a density of one for water, the formation of analcite results in a 2 per cent increase in volume.)

The analcite dikes of Quebec (Adams, 1913, p. 45) suggest that a magma existed which was capable of providing the materials to yield jadeite. The fact that some of the analcite crystals in the dike contain idiomorphic inclusions of sodic pyroxenes, nepheline, and albite is noteworthy. These brief notes are only to draw attention to many occurrences which might be regarded as potentially jadeitic.

An early suggestion was that jadeite could be produced by dehydrating analcite. Gruner (1928) heated a crystal of analcite to 700°C. and found no change in structure. This was verified by Taylor (1930) who also noted slight changes of intensities of reflections owing to the loss of the H_2O contribution. On heating at 1000°C. analcite breaks down into nepheline and albite. The relations of analcite to nepheline and albite will be treated in detail in the following sections from both a theoretical and experimental point of view.

(To Be Continued)

STRATIGRAPHIC STUDIES IN NORTHERN PERU

BERNHARD KUMMEL

ABSTRACT. Detailed measured sections of Permian, Triassic, Liassic, Neocomian, and Aptian rocks are described from the Cordillera Central, Cerro de Caya Caya, Departamento de Amazonas, Peru. The stratigraphic data presented are the bases for extensive faunal studies on the Triassic and Permian which are now being carried on. The Permian section is the most northern fossiliferous Permian section so far reported and its fusulinids indicate an early Leonard age. This is also the youngest Permian studied in Peru to date. The Triassic rocks contain the only ammonite fauna of that age yet discovered from Peru.

INTRODUCTION

WHILE in the employ of the Peruvian Government in the old Departamento de Petróleo, Cuerpo de Ingenieros de Minas* the author had the opportunity to make some stratigraphical studies in the Cordillera Central of northern Peru between the Maranón and the Utcubama Rivers. Fine sections of Permian, Triassic, Liassic, Neocomian and Aptian rocks were studied and measured in detail on the west flanks of the Cerro de Caya Caya. Steinmann (1929) had visited the area and made note of these formations including a limited discussion of some of the contained faunas. The main objective of this study was to measure and collect the unique fossiliferous Triassic rocks which crop out over a large area in the Utcubamba Valley. A preliminary report giving the stratigraphic data obtained is presented here.

The fusulinids from the Permian section were studied by T. G. Roberts (1949), and they establish well the age of these beds. Large collections from the Permian and the Triassic are in the process of study. A part of the Triassic fauna has been described by Jaworski (1922). The Triassic fauna is noteworthy in that it represents essentially the only ammonite

* The duties of this organization are now incorporated in a new agency, the Establecimientos Petroléros Fiscales, Ministerio de Fomento. The support and encouragement for this study by Sr. A. Cabrera La Rosa, Gerente of the above organization is gratefully acknowledged. The writer is grateful to Sr. Fernando Neri for his companionship and able assistance in the field. The writer also wishes to express his appreciation to C. O. Dunbar for preliminary studies on the fusulinids and to T. G. Roberts who studied and published a description of this fauna.

fauna of that age yet recorded from Peru. The fossils are silicified; approximately a ton of fossiliferous blocks of this Triassic limestone has been etched so far yielding thousands of specimens representing protoconchs to mature individuals. The fauna also contains pelecypods, gastropods, ostracods, brachiopods, and sponge spicules. This fauna represents part of the large Peruvian Triassic collections at the American Museum of Natural History, New York City, that is being studied by Newell, Haas, and the author (Science, 1947, vol. 106, p. 144).

LOCATION OF THE AREA

The Cerro de Caya Caya is part of the Cordillera Central of the Peruvian Andes and is situated on the divide between the Maranón and Utcubamba Rivers. The area of study lies entirely in the Departamento de Amazonas in northern Peru. This Departamento fronts on the great Amazon rain forest all along its eastern border. The western boundary lies well in the Cordillera Central and parallels more or less the upper course of the Maranón River. There are no roads connecting this area with the coastal regions of Peru. Under an old road building program there was projected a road from Balsas on the Maranón to the town of Leimibamba on the Utcubamba River over the Cerro de Caya Caya; however, only three kilometers were completed and those out of Leimibamba. The traveler wishing to visit the region can enter over well used and ancient mule trails that start at several points west of the Departamento de Amazonas. At the present time there is a weekly air service from Chiclayo on the coast to Chachapoyas, the capital of the Departamento. One of the most used mule trails starts at Celendin in the southwestern part of the Departamento de Cajamarca and climbs to a high divide at approximately 3000 meters above sea level directly east of Celendin; the trail follows a winding descent to Balsas on the Maranón River, at 900 meters, then begins to follow a circuitous route to the summit regions of the Cerro de Caya Caya at approximately 3700 meters; and then follows the descent to the town of Leimibamba on the Utcubamba River which lies approximately 2200 meters above sea level. The stratigraphic sections described in this report were measured for the most part along this mule trail between the summit regions

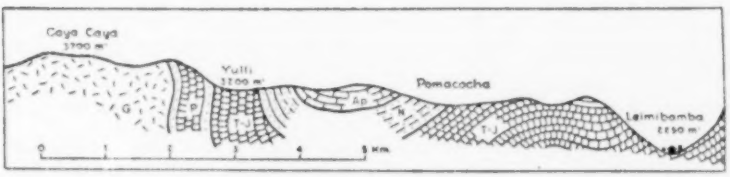
of the Cerro de Caya Caya and the town of Leimibamba. Along this sector of the trail are two valleys. The first above Leimibamba is called Pomacocha and here the Triassic and Jurassic rocks outcrop the best; the second, higher up the mountain side is called Yulli. The high northern walls of Yulli valley are formed by Neocomian and Aptian rocks; the southern walls are formed by Permian, Triassic and Jurassic rocks.

The author entered the region by flying to Chachapoyas and proceeded from there by mule to Leimibamba, with a stop over at Suta. The sections around the Cerro de Caya Caya were worked for the most part out of Leimibamba. The return trip with all the fossil collections was made with 18 mules following the trail from Leimibamba to Celendin and took three days.

STRATIGRAPHY

General Relations. The outcropping rocks of the region have a regional NW-SE strike and are in general strongly folded and faulted. The core of the Cerro de Caya Caya is pink granite overlain disconformably by Permian rocks. In the area between Caya Caya and Leimibamba the rocks are only slightly faulted and have broad open folds (Text fig. 1); however, between Leimibamba and Chachapoyas the Triassic and Jurassic rocks are badly faulted and folded. Along this latter stretch it is difficult to measure any complete sections. No conclusive evidence was obtained of the nature of the contacts between the various formations. Most contacts were seen in only small localized outcrops. However, there is no reason to believe that any angular discordances are present.

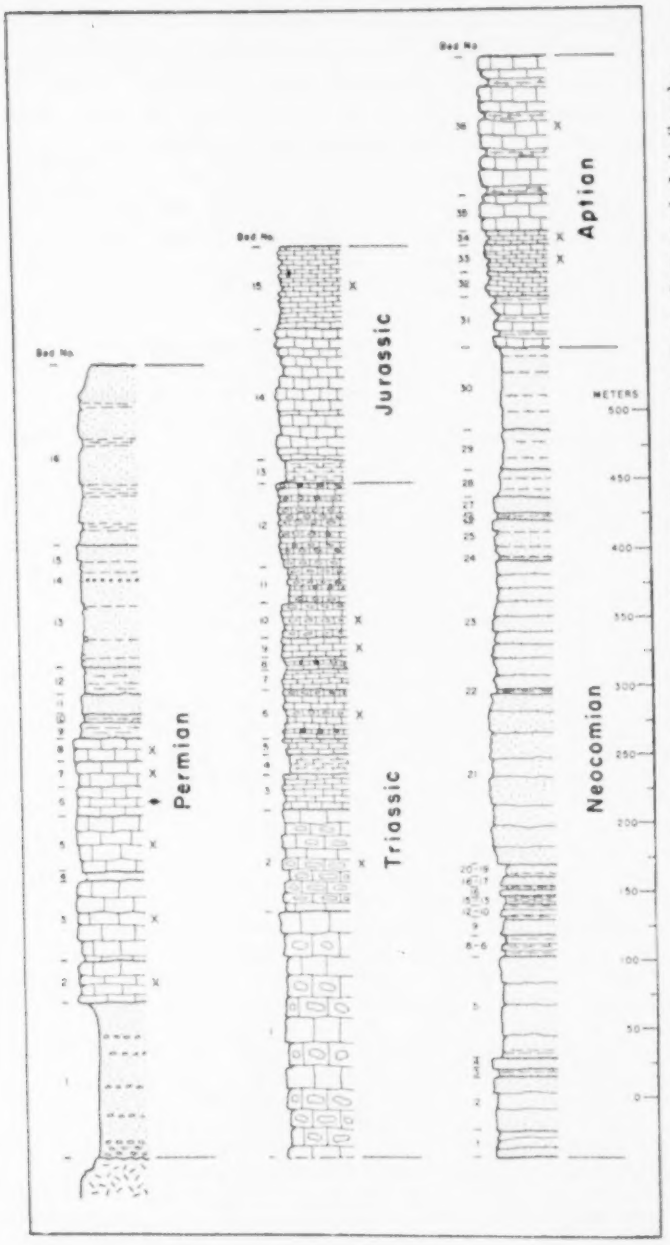
Permian. Directly overlying the pink granite forming the



Text Fig. 1. Section showing structural relations of formations between the Cerro de Caya Caya and Leimibamba (after Steinmann, 1930). G — Granite, P — Permian, T-J — Triassic-Jurassic, N — Neocomian, Ap — Aptian.

core of Cerro de Caya Caya are 589 meters of rock assigned a Permian age. The Permian sequence is composed of three main lithologic divisions. There is a lower basal conglomerate, arkose, and sandstone member predominantly red in color and 115 meters thick. This is succeeded by a thick massive limestone sequence containing myriads of silicified fossils. The fusulinids came from bed 6 (Text fig. 2) 258 meters above the base of the formation. This limestone member is 210 meters thick. Overlying the limestone member is a series of red to brown sandstone, clay-shale, and siltstone which is overlain by Triassic limestones. Fusulinids are present only in bed 6 and were identified by T. G. Roberts (1949, p. 236-238) as *Parafusulina Kummeli* Roberts; they indicate an early Leonardian age for the enclosed strata. This Permian sequence appears to be the youngest Permian section thus far recorded in Peru. Dunbar and Newell (1946) record several sections of Wolfcamp in central and southern Peru and from Bolivia (Text fig. 3). The abundant fusulinids in their strata show very close similarities with the Wolfcamp of West Texas (Dunbar and Newell, 1946). These authors give a fine summary of the present knowledge of the Permian rocks of Peru and Newell, Chronic, and Roberts (1949) have undertaken a more extensive study of the Upper Paleozoic rocks of Peru. Thompson and Miller (1949) have described several fusulinid faunas from Venezuela and Columbia and show the occurrence of Permian rocks younger than any so far reported from Peru. These authors also give an excellent summary of the previous work on South American fusulinids.

Triassic. Triassic rocks outcrop extensively along the Utcubamba valley between Chachapoyas and Leimibamba, where they have been named the Utcubamba formation by Weaver (1942). Above Leimibamba along the mule trail to Celendin in the region of Pomacocha, the Triassic rocks are very well exposed. Half way between Chachapoyas and Leimibamba is a small tributary of the Utcubamba River coming in from the east called Suta, where Steinmann obtained the silicified ammonite fauna studied by Jaworski (1922). A fine silicified fauna was obtained from the Suta locality at several distinct horizons. Unfortunately, however, the area is strongly faulted and no top or bottom of the section could be found. The section recorded here was measured at Pomacocha above Leimibamba.



Text Fig. 2. Columnar sections of formations measured between the Cerro de Caya Caya and Leimibamba.
X — fossiliferous horizons - ● - fusulinid horizon.

Permian section measured in Cerro de Caya Caya, along trail between Leimibamba and Balsas and above Yulli Valley; November 7, 1945.

Triassic limestone

Massive cliff of gray, thick-bedded, silicous limestone.

Permian	Thickness (in meters)
16. Sandstone, yellow-brown, conglomeratic in parts, with granite boulders, some interbedded red sandstone and shale beds, micaceous, mostly covered	132.00
15. Sandstone, red and yellow-brown, interbedded with brick-red silty shales, micaceous	24.00
14. Sandstone, red, conglomeratic with boulders of granite, micaceous	2.00
13. Siltstone, gray-brown to tan, massive, weathers yellow-brown on surface, contains thin interbedded units of red micaceous siltstone, partially covered	63.00
12. Siltstone, red micaceous, massive and laminated, partially covered	20.00
11. Sandstone, gray-brown, fine-grained, massive, partially covered	15.00
10. Siltstone, brick-red, clayey, micaceous, thin-bedded, partially covered	6.00
9. Sandstone, gray-brown, micaceous, medium-grained, both laminated and massively bedded, soft, partially covered	12.00
8. Limestone, gray, compact, massive, with myriads of silicified fossils	18.00
7. Limestone, brown, weathers iron-brown on surface, massive, with chert concretions, myriads of silicified fossils	18.00
6. Limestone, gray-black, compact, hard, massive, weathers light-gray on surface, contains fusulinids (*Parafusulina Kummeli* Roberts) and other silicified fossils	21.00
5. Limestone, gray and brown alternating, massive, partially covered, contains silicified fossils	42.00
4. Covered, interval occupied by stream bed	11.00
3. Limestone, brown, compact, crystalline, very massive, forming first prominent scarp past the granites, weathers dark-gray, contains myriads of silicified fossils, productids and crinoid stems the most abundant	60.00
2. Limestone, gray, finely crystalline, compact, with chert concretions, weathers dark-gray, contains myriads of silicified fossils, crinoid stems, brachiopods, etc., partially covered	30.00
1. Conglomerate, arkosic, cobbles and boulders of quartz and dark igneous rock, massive, interbedded with thick zones of red medium-grained sandstone, soft, containing some pebbles of quartz; this unit outcrops in a grass-covered and partially covered zone between the granites and the first massive limestone scarp	115.00
Total	589.00

The Triassic is composed of thick massive gray limestone in the lower part with thinner bedded units towards the top. The whole section contains abundant chert concretions and many units are very silty. Silicified fossils are present almost throughout the whole section. However, due to transportation problems only the more apparent richer beds were sampled. Jaworski (1922) assigned a Norian age to the Suta fauna listing the following species:

Text Fig. 3. Map showing location of known Permian sections in Peru. 1. Cerro de Caya Caya, 2. Ganzo Azul discovery well, 3. Yauli formation of Dunbar and Newell (1946), 4. Cerro Pirhuate, 5. Munani section, Quebrada Quishurani, 6. Straits of Tiquina.

Nevadites Lissoni Jaworski
Nevadites Sutanensis Jaworski
Anolcites Dieneri Jaworski
Sagenites aff. *quinquepunctatus* Mojs.
Rhabdoceras curvatum Jaworski
Placites op. cf. *Sakuntala* Mojs.
Monophyllites sp.
Arcestes sp.
Metasiberites annulosus Mojs.
Pseudomonotis ochotica Keys.
Nucula aff. *carantana* Bittner
Leda sp. cf. aff. *sulcellata* Muenst.
Cardita cf. *singularis* Healy
Pseudoscalites subornatus Jaworski
Eucycloscala cf. *exigua* Healy
Dentalium sp. cf. *simile* Broili

The collection on hand includes all of Jaworski's species and several more: too little work, however, has been done as yet to make any additional statement about the age of the fauna. The fauna contains predominently ammonites, with small numbers of gastropods, pelecypods, brachiopods, bryozoa, ostracods, and sponge spicules. The gastropods are being studied by Haas in conjunction with his study of the gastropod fauna from the Triassic rocks of the Cerro de Pasco region of central Peru. The pelecypods are being studied by Newell and the ammonites by the author.

This Triassic fauna is unique in that no other Peruvian and few other South American localities have yielded such an abundant ammonite fauna from Triassic rocks. The Utcubamba formation contains *Pseudomonotis ochotica* which is an Upper Triassic Norian species with a world wide distribution. It has been recorded from Norian rocks in Siberia, Alaska, Japan, Nevada, California, Oregon, Columbia, Ecuador, Peru, New Zealand, New Caledonia, the Indian Archipelago, and in the Crimea. In Peru (Text fig. 4) *Pseudomonotis* has been recorded at Huaira in the Chinchao valley northeast of Huanuco (Steinmann, 1929), near Concepcion and Tarma (Harrison, 1940), at Carhuamayo and Cerro de Pasco (Boit, 1940, 1945), and just north of Olmos, east of the Sechura desert in northern Peru (A. A. Olsson, personal communication). *Pseudomonotis* is recorded from the basal part of the Santiago formation in eastern Ecuador (Tschopp, 1945, 1948).

Triassic-Jurassic Limestone measured at Pomacocha, along trail between Leimibamba and Balsas, October 29, 1945.

	Thickness (in meters)
Liassic	
15. Limestone, black, bituminous, thin-bedded, slabby, brittle with large limestone concretions, lithographic in part, interbedded with some dark-brown calcareous shaley siltstone, few fossils present	60.00
14. Limestone, gray, regular and massively bedded, mostly covered; some drag folds and reverse dips present in this part	96.00
13. Shale, gray-brown, calcareous, interbedded with 25 cm. to 50 cm. beds of brown silty limestone, partially covered	18.00
Total	174.00
Triassic	
12. Limestone, gray-black, regular but wavy bedded, with much chert concretions, weathers tan and gray, very hard, no fossils	62.00
11. Covered, on opposite side of valley appears to be the same as above	26.00
10. Limestone, gray black, regularly bedded, cherty, contains silicified fossils, mostly covered	26.00
9. Limestone, dark-gray, massive, compact, contains silicified fossils in several distinct horizons, also with scattered fossils throughout	15.00
8. Limestone, dark-gray, compact, weathers tan and light-gray on surface, contains bands and rounded masses of chert, bedding irregular	9.00
7. Limestone, dark-gray, weathers gray and tan, silty, in irregular beds 25 cm. thick, weathers in pitted and streaked surface	14.00
6. Limestone, dark-gray, in wavy beds 20 cm. thick, with frequent 25 cm. to 50 cm. beds of chert, weathers light-gray, contains some silicified fossils, upper part partially covered	36.00
5. Limestone, dark-gray, compact, hard, in beds 25 cm. thick, alternating with thin units of tan silty marl	12.00
4. Covered, shaly and thin-bedded limestone	14.00
3. Limestone, gray, in even regular beds 25 cm. to 50 cm. thick	26.00
2. Limestone, tan, hard, compact, weathers gray, contains abundant chert concretions, massive in beds 1 to 2 meters thick, contains some silicified fossils	75.00
1. Limestone, steel-gray to blue-gray, extremely massive, forms principal scarp in Triassic-Jurassic section, contains abundant hard chert concretions, also chert beds, limestone hard, compact, weathers gray, no fossils seen	180.00
Total	495.00

The small scattered outcrop areas of the Peruvian Triassic include strata of Ladinian, Karnian, and Norian age. No Skythian, Anisian, or Rhaetic rocks have as yet been recorded from Peru. The Ladinian is represented in a limestone sequence in the Cerro de Acrotambo (Korner, 1937). The Norian limestone of the Cerro de Pasco region has been reported frequently; however, this rock sequence has not been well documented by stratigraphic and paleontologic data (W. F. Jenks, personal communication). The distribution of the Norian rocks has been referred to above. It is hoped that the present paleontological studies being carried on with the extensive Peruvian Triassic material at the American Museum will add greatly to our present meager knowledge of the Triassic of Peru.

Liassic rocks: The oldest Jurassic rocks outcropping in Peru are found in the Utcubamba valley. Numerous isolated exposures of these rocks can be seen between Chachapoyas and Leimibamba; however, structural complications make the measurement of detailed stratigraphic sections very difficult or impossible. Overlying the cherty Triassic limestones at Pomacocha, above Leimibamba, are 170 meters of black limestone and calcareous shales assigned a Liassic age. Unfortunately no fossils were found in this particular region.

Steinmann (1929) recognized Hettangian and Sinemurian rocks in the Utcubamba valley. Weaver (1942) named the Hettangian rocks the Chilingote formation and the Sinemurian rocks the Suta formation. The Chilingote formation consists of dark limestones, dolomitic in part, and calcareous shales and the Suta formation consists of thin-bedded limestones and interbedded shale beds. In the Pomacocha section it appears that bed 13 (Fig. 2), and part of bed 14 belong to the Chilingote formation whereas the remainder of bed 14 and bed 15 belong to the Suta formation. Bed 14 contained structural complications and was too covered to be accurately subdivided in the field.

Cretaceous. Sandstones of Neocomian age are well exposed along the mule trail from the intermountain valley of Pomacocha to Yulli. The trail ascends at a rapid rate following a very circuitous route and in many places over the more friable and softer sandstone units is more than six feet deep, having been worn down through the constant passage of mules and horses over a long period of time. The rocks assigned a Neo-

comian age are 589 meters of coarse to fine-grained, heavily cross-bedded sandstone with much shale interbedded. They overlie Jurassic limestones; the contact conditions were not observed but appear to be conformable. The sandstone is for the most part in very massive units, white to gray-white, and usually weathers yellow-brown on the surface. The sandstones contain abundant thin lenses and scattered masses of quartz pebbles, very characteristic of the Neocomian in many other

Text Fig. 4. Map showing location of principal Triassic outcrop areas in Peru. 1. Suta, 2. Cerro de Caya Caya, 3. Chinchao valley, 4. Cerro de Pasco, 5. Carhuamayo, 6. Concepción and Tarma region, 7. Cerro de Acrotambo.

places in Peru. Throughout the whole section there are numerous thin clay shale beds. Some of the shale beds are laminated with fine-grained sandstone and contain abundant mica flakes and plant fragments. The shale beds are more numerous in the lower half of the formation. No plant material well enough preserved for identification was found. The upper part of the Neocomian sandstone forms a broad terrace upon which rests a thick sequence of Aptian limestone.

Neocomian rocks have a very wide distribution in Peru. Their distribution in Peru has been well summarized by Weaver (1942). Lower Neocomian rocks are continental sediments in eastern and central Peru; along the coast in the vicinity of Lima these beds contain some marine members also. The Barremian (Upper Neocomian) in many places in central Peru is composed of shales and limestones containing marine fossils. The Neocomian rocks of the Caya Caya region are considered to be at least partly correlative with the thick Lower Cretaceous sandstones of Central Peru (McLaughlin, 1924; Weaver, 1942, etc.) and to the lower part of the Oriente formation of eastern Peru (Kummel, 1946, 1948).

Overlying the Neocomian sandstone are 212 meters of light-gray limestone, argillaceous in part. The lower half of the formation is in thin-bedded, partly shaly units; the upper part is heavy, massive, gray limestone beds having a conchoidal fracture. Throughout the sequence fossils are scarce and poorly preserved. These rocks are assigned an Aptian age on stratigraphic position only and may even include some Albian rocks.

Lower Cretaceous section measured at Yulli, along trail between Leimibamba and Balsos, November 8, 1945.

	Thickness (in meters)
Aptian	
36. Limestone, light-brown to tan, compact, hard, massive, with conchoidal fracture, forms huge scarp, has some 1 to 2 meter shaly marl beds, fossils throughout but few and poorly preserved	100.00
35. Limestone, gray-brown, massive, forms prominent scarp, some fossils present, weathers gray on surface	27.00
34. Limestone, light-gray, thin-bedded, hard, with conchoidal fracture, weathers tan and gray on surface, some fossils present	10.00
33. Limestone, gray, argillaceous, in regular beds 10 cm. to 25 cm. in thickness, contains poorly preserved pelecypods, echinoids, weathers grayish tan	20.00

	Thickness (in meters)
32. Limestone, light-gray, argillaceous, shaly and thin-bedded, weathers tan on surface	18.00
31. Covered, probably argillaceous limestone, shaly, exposed in part on other side of syncline	37.00
Total	212.00

Neocomian

30. Covered, unit very soft, forms low platform beneath Aptian limestone	60.00
29. Sandstone, white-gray, fine-grained, massive and soft, contains much carbonaceous material and plant fragments	30.00
28. Sandstone, white and yellow-brown, fine-grained, and black shale units laminated and thinly bedded, contains mica flakes and plant fragments	18.00
27. Sandstone, iron brown, medium-grained, with iron concretionary beds, massive	12.00
26. Sandstone, fine and medium-grained, thin bedded and shaly, with interbedded units of siltstone, contains plant fragments and mica flakes	5.00
25. Sandstone, white, mottled yellow-brown, medium-grained, with lenses of coarse pebbles, soft, massive, cross-bedded, contains thin beds of gray shale	27.00
24. Shale, yellow-green, clay	2.00
23. Sandstone, white to yellow-brown, fine-grained, interbedded with units of coarse gray sandstone, relatively soft, partially covered	95.00
22. Shale, gray-white, silty, hard, well bedded, interbedded with fine-grained sandstone, contains plant fragments and mica flakes	2.00
21. Sandstone, white to yellow-brown, very massive, coarse to fine grained, with lenses of pebbles, contains iron concretions, forms high prominent scarp	125.00
20. Siltstone, gray-brown, massive, soft	6.00
19. Shale, yellow-gray, clay	2.00
18. Sandstone, white to yellow-brown, medium to coarse grained, cross-bedded, contains abundant pieces of fossil wood and plant fragments	8.00
17. Shale, gray, silty, hard	2.00
16. Sandstone, white to yellow-brown, coarse, with pebble lenses, massive, cross-bedded, poorly sorted, has interbedded zones of very fine-grained sandstone, contains fragments of fossil wood	5.00
15. Shale, yellow-green	2.00
14. Shale, red	2.00
13. Shale, yellow-green, clay	2.00
12. Sandstone, yellow-brown, very fine-grained, thin-bedded and laminated, contains mica flakes	3.00
11. Sandstone, white, medium to coarse grained, cross-bedded, massive and soft	5.00
10. Sandstone, gray-brown, fine-grained, thin-bedded and laminated, with interbedded units of gray shale	2.00

9.	Sandstone, white, mottled yellow, medium grained, with lenses of coarse pebbles, weathers gray on surface, unit relatively soft	12.00
8.	Shale, green	6.00
7.	Sandstone, very fine-grained, thin-bedded and laminated, contains lenses of coarse pebbles, with interbedded units of green shale	5.00
6.	Shale, red, mottled gray	4.00
5.	Sandstone, gray-white, very fine grained, weathers yellow-brown at surface, lower four meters thin-bedded and laminated with mica flakes, upper part massively bedded, white, with pebbles up to 1 cm. in diameter, some thin zones impregnated with a dry, black, bituminous material, unit in general soft, forming low platform	75.00
4.	Sandstone, gray-white, coarse, massive, cross-bedded	8.00
3.	Sandstone, gray-white, fine-grained, thin-bedded and laminated, interbedded with gray-blue shale, contains mica flakes and plant fragments	5.00
2.	Sandstone, white and yellow-brown, massive, cross-bedded, coarse, with iron concretions and lenses of quartz pebbles, partially covered	39.00
1.	Sandstone, yellow-brown, massive, cross-bedded, contact zone covered, cannot tell for sure relationship	20.00
	Total	589.00

References

Bolt, B., 1940. Lineas generales de la Geología Estratigráfica de la region de Cerro de Pasco: Actas de la Acad. de Cienc. Exact. Fisic. y Natls. de Lima, año 2, vol. 11, nos. 431, 432, pp. 135-162, 277-302.

———, 1945. Geología post-carbonica de Carhuamayo: Actas de la Acad. de Cienc. Exact. Fisic. y Natls. de Lima, año 8, vol. 8, pp. 69-85.

Dunbar, C. O., and Newell, N.D., 1946. Marine early Permian of the Central Andes and its fusuline faunas: Am. Journ. Sci., vol. 244, pp. 377-402, 457-491.

Harrison, J. V., 1940. Nota preliminar sobre la Geología de los Andes Centrales del Peru: Bol. Soc. Geol. Perú: vol. 10, pp. 1-53 (In Spanish and English).

———, 1943. Geología de los Andes Centrales en parte del Departamento de Junín, Perú: Bol. Soc. Geol. Perú, vol. 16, pp. 1-97.

Jaworski, E., 1922. Die Marine Trias in Sudamerika. Beitr. z. Geol. u. Pal. u. Sudamerika, 26. Neues Jahrb., Beilage-Band 47, pp. 93-200.

Korner, K., 1937. Marine (Cassianer-Raibler) Trias am Nevado de Acrotambo (Nord-Peru): Palcontographica, vol. 86, pp. 145-240. incl. map.

Kummel, B., 1946. Estratigrafía de la Región de Santa Clara. Bol. Soc. Geol. Perú: vol. 14, pp. 133-144.

———, 1948. Geological Reconnaissance of the Contamana Region, Peru: Geol. Soc. America Bull., vol. 59, pp. 1217-1265.

McLaughlin, D. H., 1924. Geology and physiography of the Peruvian Cordillera, Departments of Junin and Lima: Geol. Soc. America Bull., vol. 35, pp. 591-632.

Newell, N. D., Chronic, B, J., and Roberts, T. G., 1949. Upper Paleozoic of Peru, New York, 241 pp.

Steinmann, G., 1929. Geologie von Peru, 1-448, pls. 1-9, Heidelberg. (Spanish edition, Geologie del Peru, Heidelberg, 1930.)

Thompson, M. L., and Miller, A. K., 1949. Permian fusulinids and cephalopods from the vicinity of the Maracaibo Basin in northern South America: Jour. Paleontology, vol. 23, pp. 1-24.

Tschopp, H. J., 1945. Bosquejos de la geología del Oriente Ecuatoriano: Bol. Inst. Sudamericano del Petróleo, vol. 1, pp. 466-484.

———, 1948. Geologische Skizze von Ekuador: Bull. d. Ver. Schweiz. Petroleum geol. und. Ing., vol. 15, no. 48, pp. 14-45.

Weaver, C. E., 1942. A general summary of the Mesozoic of South America and Central America: Proc. Eighth Amer. Sci. Congress, vol. 4, pp. 149-194.

University of Illinois
Urbana, Illinois

THE ABSORPTION OF INFRARED RADIATION BY CLAY MINERALS

W. D. KELLER AND E. E. PICKETT

ABSTRACT. Infrared absorption spectrograms by pulverized minerals of the kaolin, montmorillonite, and illite groups in the 2 to 15 micron wave length bands are shown. The kaolin minerals have a distinctive absorption but those from the other groups are less clearly defined. Spectrograms of gibbsite, brucite, quartz, opal, and muscovite are shown because of their structural relationships to the clay minerals.

INTRODUCTION

VARIOUS techniques, such as optical, chemical, thermal, and structural methods, have been used to determine and differentiate clay minerals. Another tool, infrared absorption by the pulverized clay minerals has been proposed (Keller, 1948). Although this technique is still in the exploratory stages enough information has been accumulated from numerous empirical measurements on clay minerals to present some typical patterns characteristic of them. The preliminary report will also supply information about which inquiries have been received. It should be realized that only a beginning in the work has been made, and only qualitative results have been obtained. Instrumentation needs to be improved, and after more measurements are made on various different mineral groups probably some definite assignment of absorption peaks to specific atomic groups will be possible. Quantitative methods are still before us.

The absorption of infrared radiation has been utilized as a powerful determinative and analytical tool by chemists, especially in work on organic compounds. So characteristic are the absorption bands within the 2-15 micron wave length spectrum of certain chemicals that they may be "finger printed" by their absorption spectrograms. The possible application of the technique to mineral determination has not been tested, particularly not for pulverized minerals like clays, and therefore the measurements reported herein constitute in part a trial of the applicability of the method to pulverized minerals as well

as a report on the properties of clay mineral specimens. Some preliminary work on the absorption of infrared by pulverized silica minerals has been reported (Keller and Pickett, 1949).

The principle involved in the selective absorption of infrared radiation depends upon the fact that the atoms of molecules are continuously in vibration at frequencies which fall within those of the infrared range (10^{13} to 10^{14} cycles per second) and that incident infrared radiation may be absorbed wholly or in part through interaction with the vibrating atoms. Moreover, in the infrared range there are absorptions correlating with the slower rotations of the molecules or the massive lattice vibrations of crystals. Although discrete "molecules" seldom exist in the crystal structure of most minerals, insofar as characteristic absorptions may be found, even empirically, for minerals, the basis for the results is sound.

The absorption frequency of simple or highly symmetrical molecules may be calculated approximately by the equation:

$$\nu = \frac{1}{2\pi c}\sqrt{\frac{k}{u}}$$

Where ν is the frequency in $cm.^{-1}$, c is the velocity of light, u is the reduced mass of the vibrating atoms, and k is the force constant which exists between the atoms. The formula has been simplified by reduction of constants, etc., in the concise and lucid introductory treatment of the subject by Barnes, Gore, Liddel and Williams, in their "Infrared Spectroscopy", but nevertheless, many chemical compounds, and certainly most minerals do not represent simple molecules, and it therefore lies beyond our present ability to calculate *a priori* their absorption characteristics. To this point, Barnes *et al.*, write:

"Although the mathematical approach has been of great value when applied to simple or highly symmetrical molecules, most of the information derived from infrared spectra is obtained by the application of the empirical method. This method consists of comparing the spectra of the largest obtainable number of different molecules having a common atomic group. By a process of elimination, it is often possible to find an absorption band whose frequency remains constant throughout the series. The presence, in an unknown, of an absorption at this frequency may reasonably form the basis for a guess

that the particular atomic group is present. Confidence in this method can be obtained only by successful applications in a large number of cases."

The apparatus used in these measurements is a Beckman Model IR-2 infrared spectrophotometer. Briefly, infrared radiation from a rich source is dispersed by a rock salt prism into a spectrum from which relatively narrow wave length bands are selected and transmitted along a path to a sensitive thermocouple. The intensity of the radiation transmitted is measured with the sample, and without it, in the absorption chamber, and the per cent transmission obtained thereby. High sensitivity of the instrument is achieved by suitable electronic amplification. The current infrared spectrometers embody highly advanced improvements over the apparatus which was available only a few years ago. Many of the older measurements of infrared absorption have been revised.

In this study, from 5 to 10 milligrams of the finely pulverized mineral was stirred and dispersed in 2 drops of Nujol (medicinal mineral oil) which filled the absorption chamber. The latter consists of rock salt plates which are separated by shims of variable and selected thicknesses, and held together by a metal frame. Nujol has been used as a suspending medium because it has a satisfactory viscosity, because its index of refraction lessens the scattering reflectance from the mineral particles, and because its own absorption spectrum is relatively simple. It should be recognized that the indices of refraction of both Nujol and a dispersed mineral may be radically different in the infrared range than they are in the visible spectrum. Regarding the absorption spectrogram of the suspending medium, it has been suggested that a single pure substance which could be purified chemically and reproduced closely might be preferred as a suspending medium to one like Nujol which is a complex mixture. Theoretically this is correct, but practically no pure liquid is known which has a simple absorption spectrum and also possesses the other properties which are desired for the infrared work. Because Nujol is a mixture, many tiny absorption peaks of individual constituents are averaged out, and the curve is flat enough that absorptions occurring within the susupended mineral show up.

About four hours are required to make a run and plot it.

After this manuscript had been prepared for publication it was shown by the laboratory of the Carter Oil Company* that improved spectrograms in the higher wave lengths can be obtained by grinding the particles to sizes less than the wave lengths of the radiation used. The writers obtain better resolution in the OH absorption band using Nujol, but confirm from a few runs that the resolution at higher wave lengths is superior as run by Carter Laboratory. Absorption peaks may also be made to appear sharper if the horizontal axis is shortened in relation to the vertical, but maximum detail is maintained with ample length of horizontal axis.

EXPERIMENTAL RESULTS

An absorption graph of Nujol alone in the specimen chamber is shown in figure 1. Along the base of the abscissa is plotted the wave length of the radiation in microns and along the top is the corresponding frequency in wave numbers or reciprocal centimeter. Transmission of radiation in per cent is plotted on the ordinate. Nujol is relatively transparent to most infrared radiation, transmitting from 80 to 90 per cent over most of the spectrum. Slight absorption occurs at approximately 2.3 and 2.4 microns, and almost complete absorption (opacity) for a band at about 3.43 microns in wave length. Lesser absorption occurs from 3.6 to 3.72 microns and pronounced absorption at 6.86 and 7.28 microns. Numerous slight absorptions extend over wave lengths to about 11.0 microns and another prominent peak occurs at 13.86 microns. This "background" of absorption is unavoidably present in every measurement where a mineral was immersed in Nujol. It may be "subtracted" from the mineral graph to obtain the absorption characteristics of the mineral. The telltale characteristics of a positive nature of an irradiated compound are its absorption "peaks" or depressions. High transmission bands may be characteristic of certain compounds, but they constitute evidence of a negative type.

It may be recalled here that chemists have found OH groups absorb at different wave lengths between 2.7 and 3.1 microns depending upon the degree of hydrogen bonding of these groups with each other or with other O atoms in the lattice.

* Personal communication from Parke Dickey, 1949.

Where OH groups are held independently, *i.e.*, monomeric, within a crystal lattice the absorption is at about 2.75 microns. Where two or more OH groups are sufficiently close together, the hydrogen of the OH groups may assume an oscillating position between two oxygen atoms with the formation of a resonating bond between both oxygen atoms simultaneously, the so-called hydrogen bond. The dimeric groups absorb at about 2.85 microns and polymeric groups at about 2.95 microns. Evidence from minerals indicates that the absorptions for the polymeric bonding may extend to perhaps 3.1 microns. Free water, H_2O, absorbs in the 6.0 to 6.1 micron range, in addition to the 2.7 to 2.9 micron band. Many other absorption bands have been correlated with chemical bonds (Barnes *et al.*, 1944; Randall *et al.*, 1949) but most of these are not applicable to minerals. If mineralogy from infrared data is developed it may require a considerable backlog of factual data before generalizations can be accurately made (as was the case with organic chemistry).

INFRARED SPECTROGRAMS OF CLAY MINERALS

The kaolin group. Infrared absorption spectrograms typical of kaolinite, dickite, halloysite and endellite are shown in figure 2. Nos. 14, 70, 71, and 72 are of kaolinite clays from Georgia, South Carolina, Nevada, and California respectively. The infrared absorption of kaolinite is characterized by "free" hydroxyl absorption at about 2.75 microns (commonly 2.72 microns) and a comparatively lesser amount of ill-defined hydrogen bonded hydroxyl up to 3.1 microns The band between 3.1 and 7.55 microns is relatively featureless, except that free water, H_2O, may or may not be shown at about 6.1 microns. Absorption begins at about 8.1 microns and increases regularly in intensity to about 8.95 microns. Another peak of slightly greater absorption occurs at about 9.15 microns. Still higher absorption peaks occur at about 9.54 and 9.95 microns, whereupon transmission increases up to 10.46 microns. Two more pronounced absorptions occur at about 10.75 and 11.0 microns. Transmission (transparency to the band) increases as the radiation lengthens to about 12.2 microns. At higher wave lengths, notable absorptions occur at about 12.7, 13.4, and 14.5 microns.

Spectrograms of numerous other kaolinite samples show high similarity to these illustrated. The absorptions are so consistent that confidence in recognition of a kaolin group from its infrared spectrogram is soon established. Pronounced free OH absorption correlates well with the kaolinite crystal structure as interpreted from X-ray diffraction data.

Miloschite, No. 71, for example, appears from infrared data to fall within the kaolin group, confirming prior evidence (Grim and Rowland, 1942; Kerr and Hamilton, 1949). The commercial Edwin #2 clay, spectrogram No. 72 from California likewise shows kaolinite infrared absorption.

Dickite shows the same general type of infrared absorption as does kaolinite, and cannot be differentiated from it with certainty at the present stage of our measurements. No. 65 shows very pronounced monomeric OH absorption at 2.72 microns which was lost upon calcination at 780°C. for 14 hours (see 65A). The characteristic absorption of the raw clay from 7.5 to 15 microns has also been obliterated or subdued after the 780° calcination, which likewise breaks down the crystal structure. Obviously the bonds between silica, alumina, and hydroxyl groups are responsible for the several absorptions shown by the raw clay but their specific assignment is not now known.

Dickite No. 69 shows less intense OH bonding than did No. 65. Various intermediate intensities of absorption in the 2.75 band have been observed on other dickites.

Endellite, No. 3, is characterized by pronounced absorption at 2.8 microns, due to free OH groups, and at 3.0 and 3.2 microns, due to hydrogen-bonded hydroxyl. At higher wave lengths the absorption of endellite parallels that of kaolinite but it is more subdued. The endellite sample was prepared by grinding under water endellite clay still wet with quarry moisture, drying sufficiently at room temperature and irradiating immediately. Another sample of powder which was "dried" in an atmosphere of 80 per cent relative humidity for two weeks gave the same absorption curve as the one shown. Molecules of interlayer water sheets in endellite, as postulated by Hendricks, are linked by polymeric bonds, and are linked to O of silica tetrahedra by hydrogen bonds of a slightly different type. Infrared absorption is in accord.

Halloysite, No. 73, shows strong OH absorption at 2.74

microns but notably less in the higher hydroxyl bands. This is in keeping with its lower water content than endellite.

As has been stated previously, we lack information on the correlation between the absorption peaks and the chemical bonds responsible for them. However, it may be suggested that the peaks occurring at 12.7 and 14.5 microns in kaolinite may arise from silica tetrahedra, or a variety of silica structure, because pulverized quartz shows infrared absorption peaks at 12.6 and 14.5 microns (Keller and Pickett, 1949). Other assignments may be speculated but do not justify printing.

The montmorillonite group. Infrared spectrograms of montmorillonite group minerals are shown in figure 3. A Ca montmorillonite, No. 43, exhibits free OH at 2.72 microns, and well-defined hydrogen bond peaks at 2.91 and 3.1 microns. Strong absorption occurs between 8.0 and 10.3 microns, above which more radiation is transmitted. Smaller absorption peaks occur at 11.0, 11.8, and 13 microns.

Na montmorillonite, No. 45, shows less well-defined hydrogen-bonded OH than does its Ca analogue. Other specimens of Na and Ca montmorillonite similarly indicate that the absorptions of the latter are more sharply defined than those of Na montmorillonite. A possible reason for this may be that the interlayer water in the Na, swelling type, of montmorillonite has greater mobility of movement than in the more tightly bonded Ca montmorillonite. At wave lengths above 7.5 microns the absorptions of the two clays are usually similar.

Beidellite, No. 9, from Creede, Colorado, and No. 12, a H beidellite from Missouri Putnam soil colloid, show spectrograms like Ca montmorillonite plus a small, but recognizable absorption peak at 10.3 microns. Insufficient samples of beidellite have been run to know if the 10.3 micron absorption is diagnostic from other montmorillonites.

Nontronite, No. 8, shows a typical montmorillonite spectrogram. We have insufficient infrared data to differentiate between the members of the montmorillonite group.

The illite group. Figure 4. Illite from Illinois gave spectrogram No. 7. The OH and hydrogen-bonded hydroxyl are prominent in the 2.75-3.2 band, similar to that in montmor-

illonite. Probably the similarity between the two mineral groups in the hydrogen-bonded OH is due to interlayer water rather than their similar 2:1 layer structure. Illite differs from montmorillonite by absorbing relatively more intensely at 12.0, 12.6, about 12.8, and 14.5 microns. Kaolinite showed peaks at 12.7 and 14.5 microns, and quartz absorbs at 12.6, 12.9, and 14.5 microns. These absorptions at similar wave lengths are probably significant but the full meaning of them is not presently clear.

Spectrogram No. 42 is of the "Sarospatak clay" from Sarospatak, Hungary, which may be a mixed layer, illite-montmorillonite clay. The OH absorption might be assigned to either of the groups. The remainder of the spectrogram is disappointingly featureless. Such an absorption is logical however, if the distribution between the two clays is such that the low intensities of absorption of each are "diluted" and subdued by the cushioning effect of the other clay. Higher resolution and higher intensity of absorption is needed; improvement or modification in apparatus is necessary.

Attapulgite. A spectrogram of the amphibole-like attapulgite, is shown in No. 16. The absorption of OH and water at 2.75-3.1 and 6.0 microns is intense. Further absorptions occur at 8.2, 8.7-8.9, 9.75, 10.2, 11.0, 11.7, 12.6, 12.95, and 14.5 microns. Some of the absorptions of attapulgite are common to montmorillonite and some to kaolinite. Only a few specimens of attapulgite have been measured and therefore insufficient empirical data are available to make a very positive statement about the constancy of the above absorptions.

Clay lattice components. Because modified sheets of silica tetrahedra, gibbsite, and brucite are present in the clay minerals, their infrared absorption spectrograms are shown in figure 5. Gibbsite, No. 22, shows both free and hydrogen bonded hydroxyl in considerable quantity. Strong absorption occurs above 8.0 microns in wave length. Brucite, No. 21, shows primarily free OH groups. This difference in structure confirms the evidence from crystal structure by X-rays as described by Bragg (1937):

"The difference" (in brucite-gibbsite structures) "lies in the way in which the layers are packed on each other. In

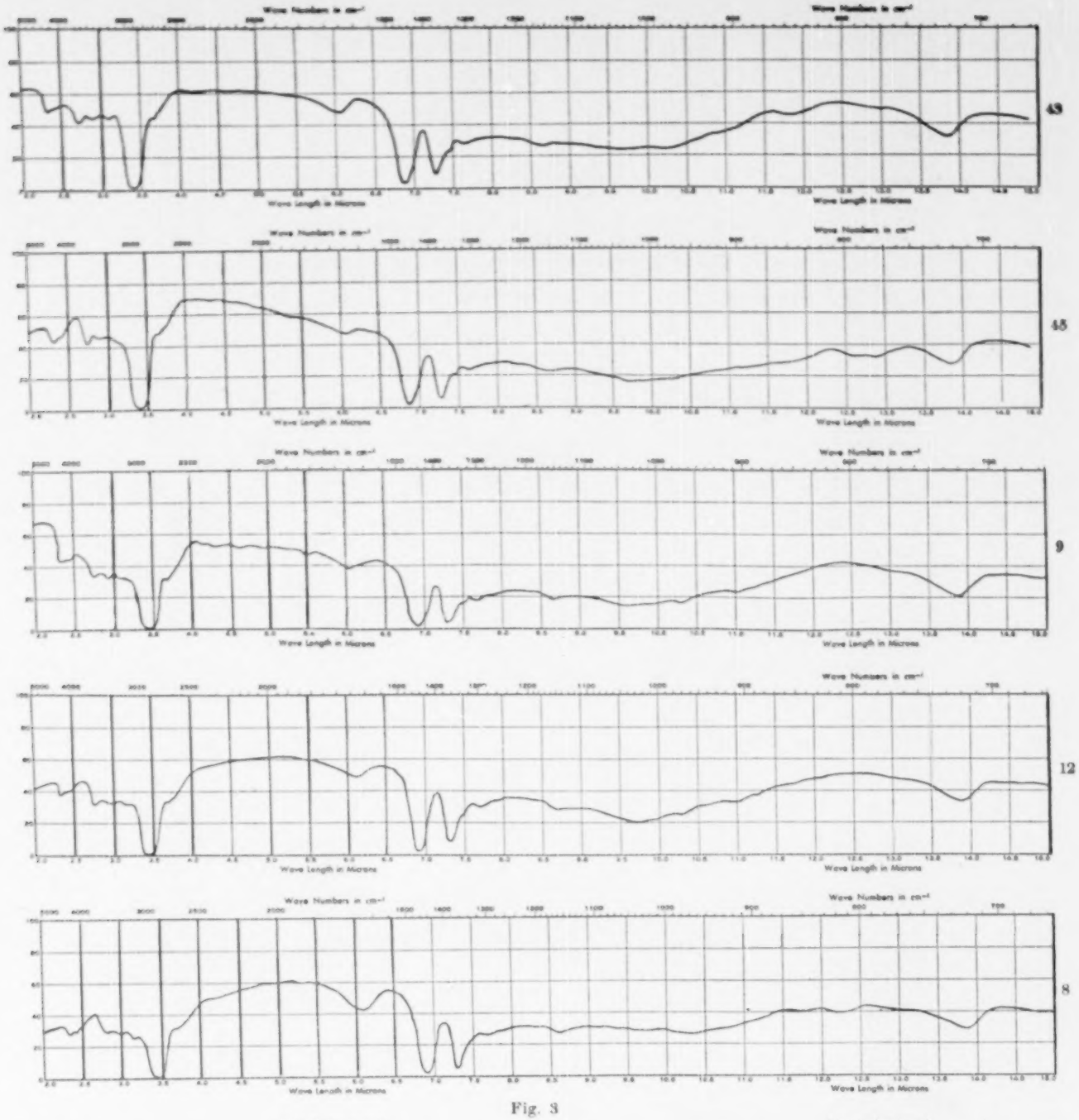
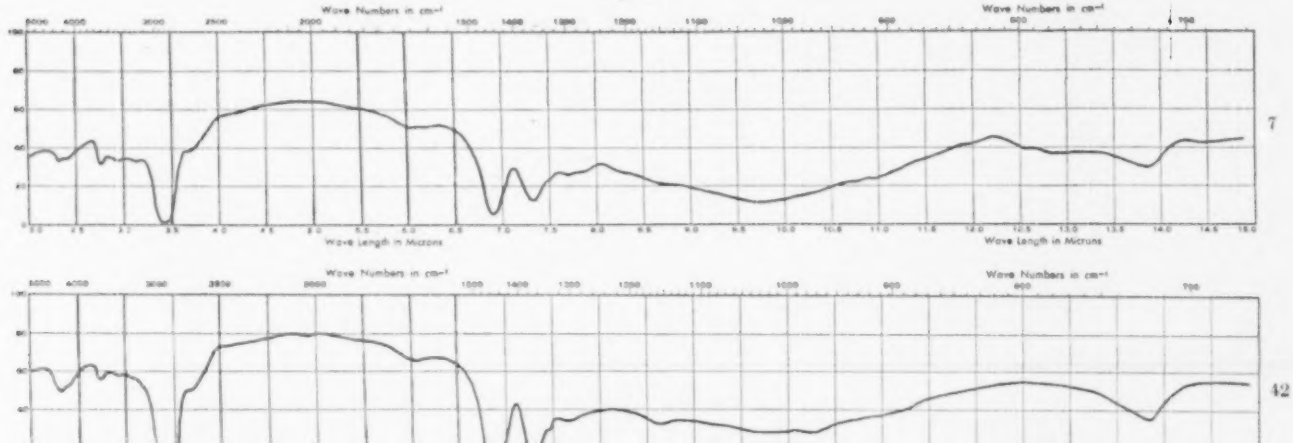
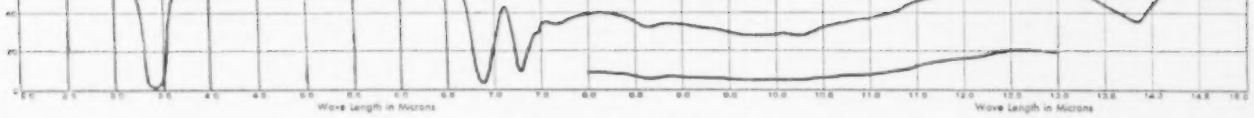
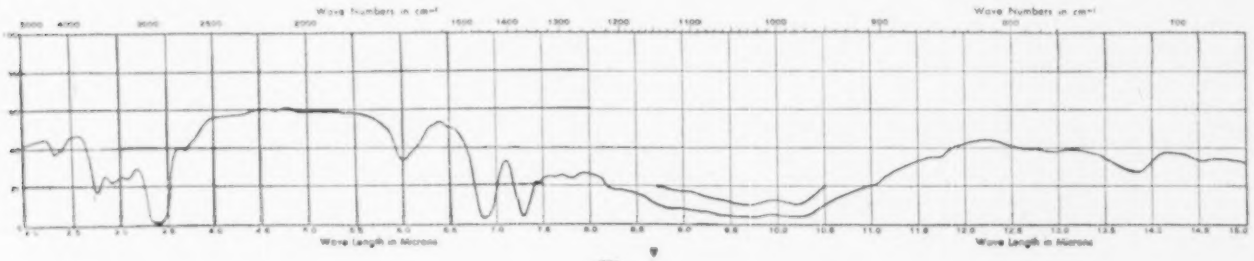

Wave Numbers in cm⁻¹
Wave Length in Microns
43
45
9
12
8

Fig. 3

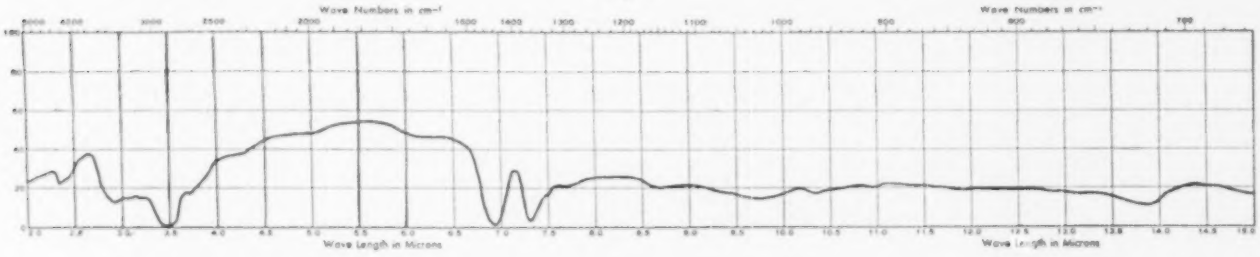

Wave Numbers in cm⁻¹
Wave Length in Microns
7
42



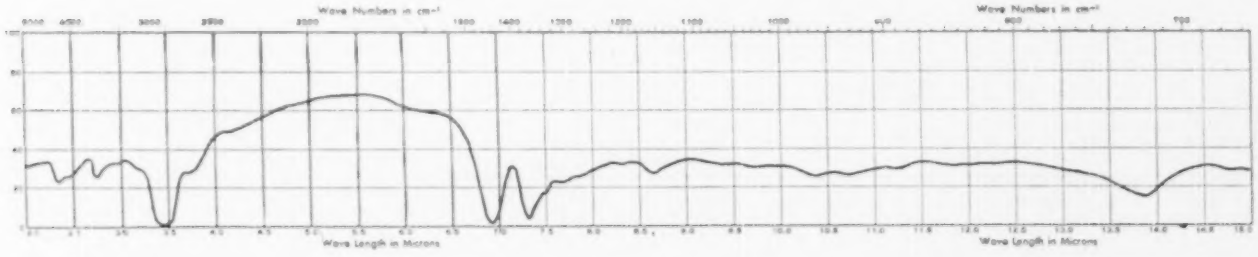


16

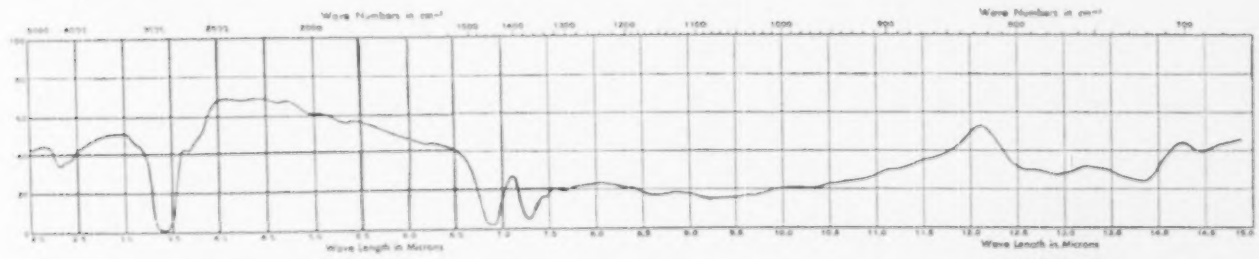
Fig. 4



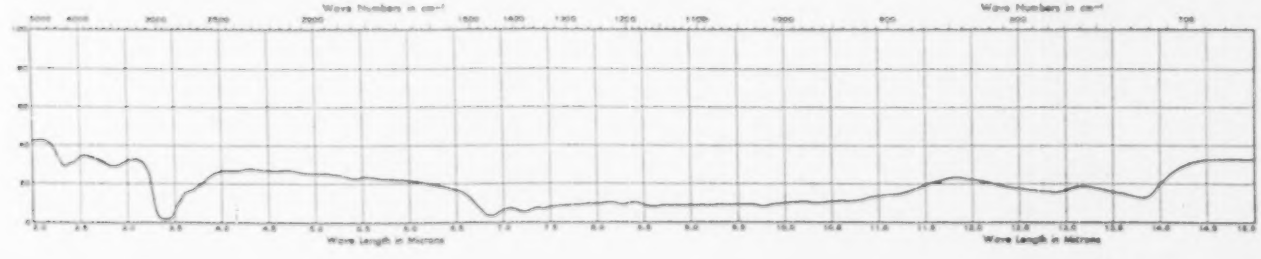
22



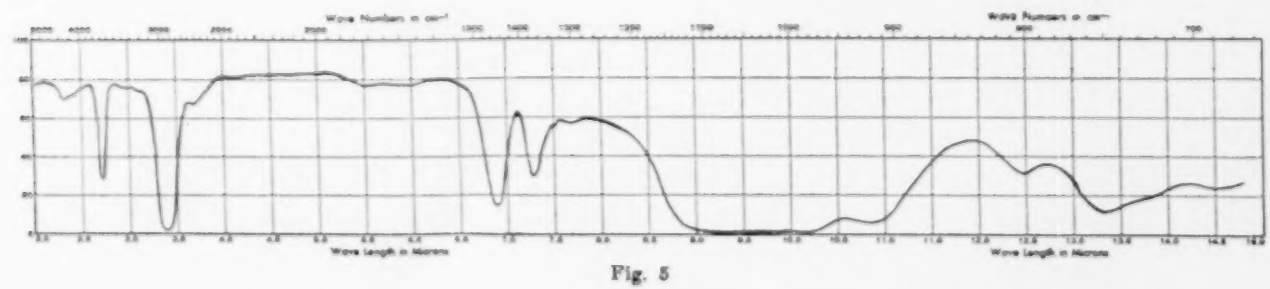
21



66



40



30N

Fig. 5

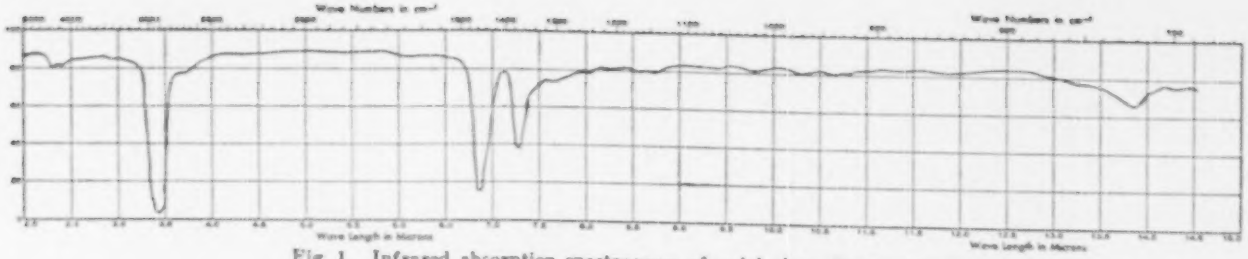
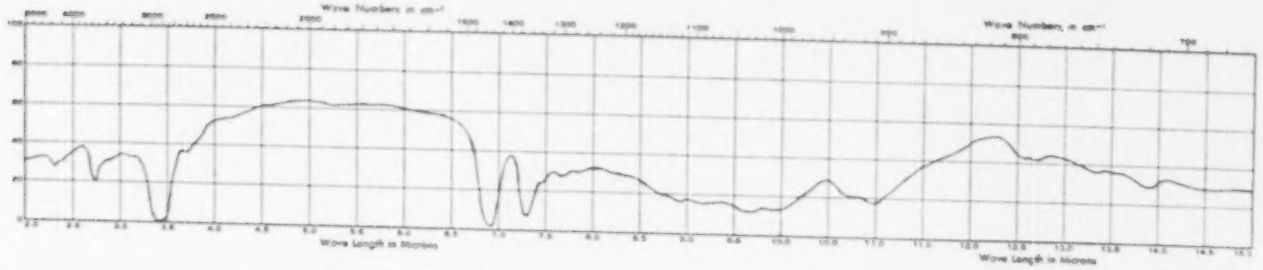
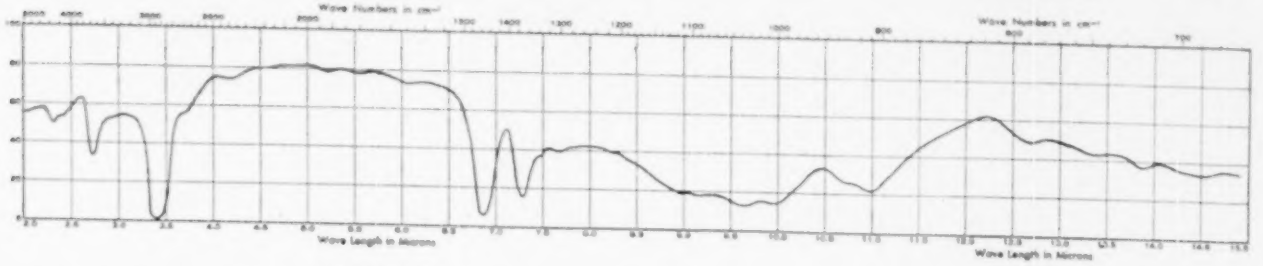


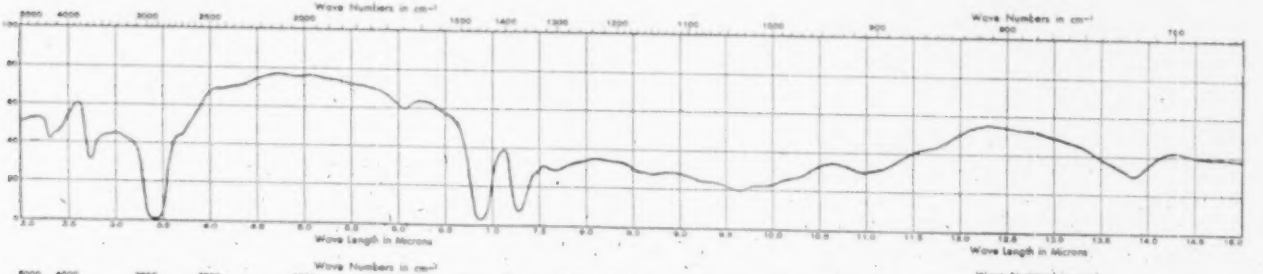
Fig. 1. Infrared absorption spectrogram of nujol alone. Per cent transmission is shown upward on the ordinate, and wave lengths in microns (also wave numbers in reciprocal centimeter) are on the abscissa.



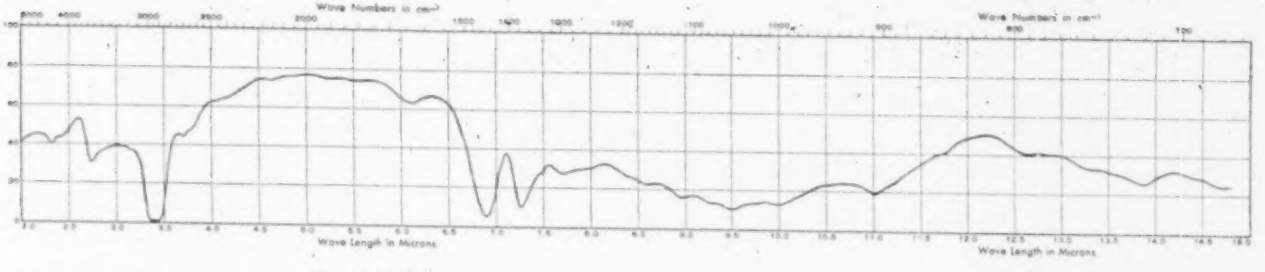
14



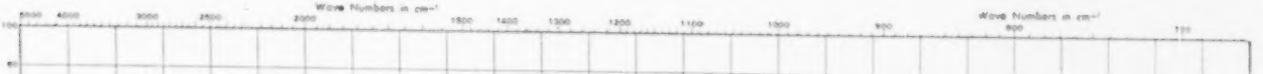
70



71



72



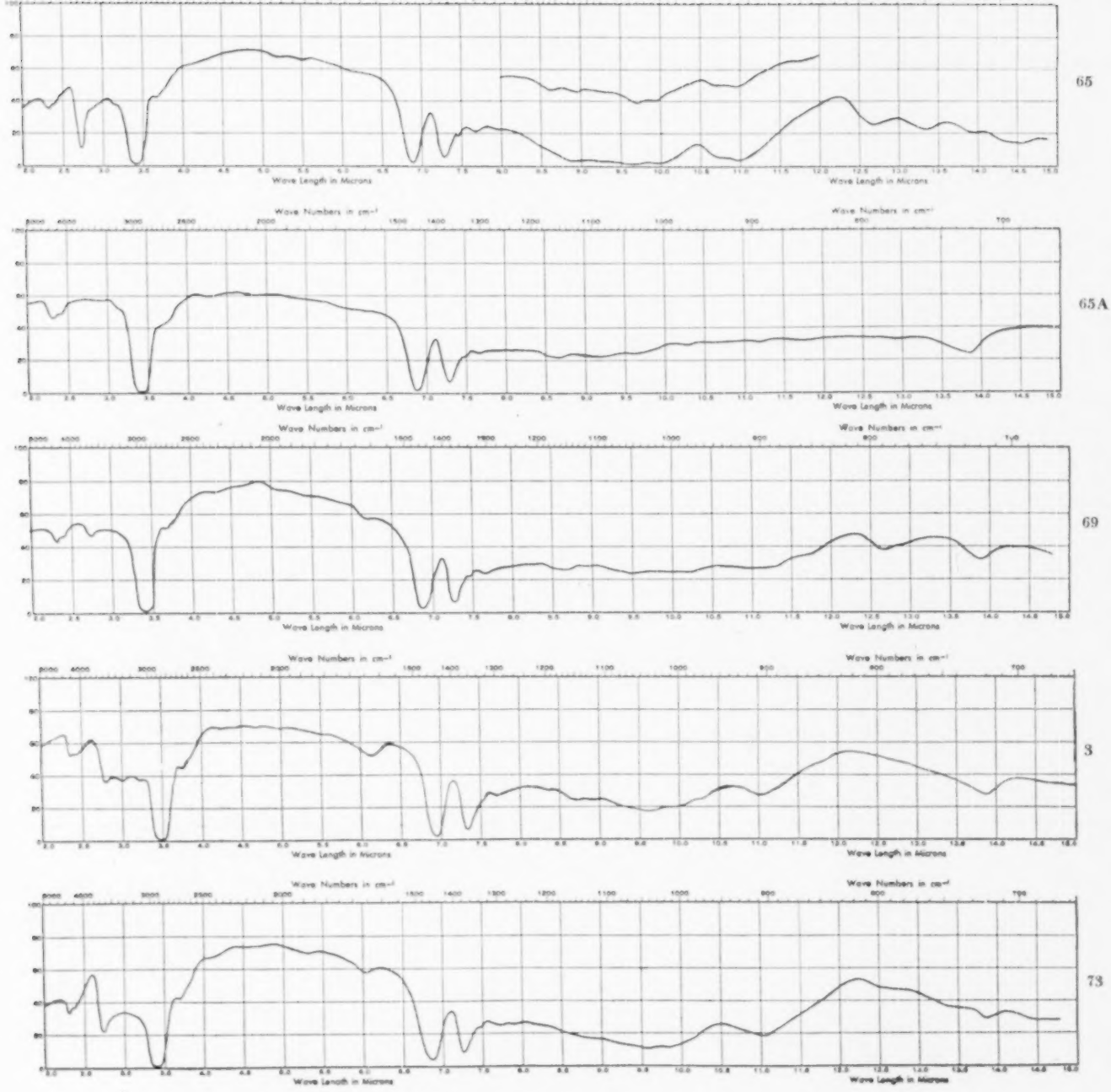


Fig. 2. Infrared spectrograms of the kaolin group of clay minerals.

No. 14. Kaolinite, Dry Branch, Georgia. From S. C. Lyons.
No. 70. Kaolinite, Langley, So. Carolina. From T. F. Bates.
No. 71. Miloschite, Ely, Nevada. From T. F. Bates.
No. 72. Edwin No. 2 clay, California. From T. F. Bates.
No. 65. Dickite, Mather Mine, Marquette Range. From J. W. Gruner.
No. 65A. No. 65 calcined at 780°C. for 14 hours.
No. 69. Dickite, Schuylkill, Pennsylvania. From T. F. Bates.
No. 3. Endellite, Indiana. From Eugene Callaghan.
No. 73. Halloysite, Avery County, No. Carolina. From T. F. Bates.

brucite, the OH sheets of neighboring layers fit into each other in a close-packed way, one OH touching three OH in the next layer. In Al $(OH)_3$ each OH of one layer is *opposite* (italics by Bragg) an OH of the next layer, as if there were a strong specific attraction of one OH for the other . . . . Brucite and hydrargillite illustrate a progressive change in the nature of the OH group which has been summarized as follows by Megaw. At one extreme when the polarizing influence of the cation is small we have $(OH)'$ groups which act much like F' ions. They pack together as if neutral towards each other, and the distance between O centres is large (3.22 Å for Mg $(OH)_2$). At the other extreme when the polarizing influence of the cation is large, there appears to be a powerful attraction between (OH) groups which draws them close together" (2.79 Å for Al $(OH)_2$). Hence the infrared absorption accords with crystal structural evidence.

Brucite absorbs strongly and with little evident characteristic fine structure above 8.0 microns.

Quartz is shown in spectrogram No. 66. No OH absorption is present. Some of the absorptions above 9.0 microns may be represented in the clay mineral absorptions, especially in kaolinite and illite. As more empirical data are assembled tentative computations of vibrational frequencies appear more logical and less conjectural. Evidence must be obtained, however, from different silica, alumina, and water linkages in various minerals. This is time-consuming and progress has not gone far.

Hyalite opal, No. 40, shows the water (2.7-3.0 microns) associated with silica. However, the clearly evident quartz absorptions, above 9.0 microns, presumably due to organized tetrahedral linkage, are not present in amorphous opal. A sheet of muscovite shows strong monomeric, free OH, in No. 30 N. Its absorptions above 8.0 microns are correlateable in part with those of the 3-layer clays, and are encouraging despite present inadequacies.

We are optimistic that infrared absorption measurements contain considerably more structural information about minerals than we are able to interpret now. The technique appears to merit more investigation.

ACKNOWLEDGMENTS

The writers are grateful to Drs. Bates, Grim, Gruner, Kerr, and Lyons who furnished samples of clay illustrated herein. The expenses for infrared measurements were defrayed under University of Missouri Research Council Grant No. 319 (302).

REFERENCES

Barnes, R., Gore, R. C., Liddel, Urner, and Williams, Van Zandt, 1944. Infrared spectroscopy, New York, Reinhold Publishing Company.

Bragg, W. L., 1937. Atomic structure of minerals, Ithaca, N. Y., Cornell University Press.

Grim, R. E., and Rowland, R. A., 1942. Differential thermal analyses of clay minerals and other hydrous materials, part 2: Am. Mineralogist, vol. 27, pp. 801-818.

Keller, W. D., 1948. Absorption of infrared radiation by clay minerals: Geol. Soc. America Bull., (abstract). vol. 59, p. 1332.

———, and Pickett, E. E., 1949. Absorption of infrared radiation by powdered silica minerals: Am Mineralogist, vol. 34, pp. 855-864.

Kerr, Paul F., and Hamilton, P. K., 1949. Preliminary report No. 1, API Project 49, Clay Mineral Standards, Am. Petroleum Inst., Dallas, Texas.

Randall, H. M., Fowler, R. G., Fuson, Nelson, and Dangyl, J. R., 1949. Infrared determination of organic structures, New York, D. Van Nostrand Co., Inc.

UNIVERSITY OF MISSOURI
COLUMBIA, MISSOURI.

Fig. 3. Infrared spectrograms of the montmorillonite group of clay minerals.
- No. 43. Ca montmorillonite, Arizona. From R. E. Grim.
- No. 45. Na montmorillonite, Wyoming. From R. E. Grim.
- No. 9. Beidellite, Creede, Colorado. From U. S. National Museum.
- No. 12. Beidellite, Putnam soil colloid, Soils Dept. Univ. of Missouri.
- No. 8. Nontronite, near Troy, Idaho. Col. with V. E. Scheid.

Fig. 4. Infrared spectrograms of illite and attapulgite.
- No. 7. Illite from Illinois.
- No. 42. Clay from Sarospatak, Hungary. From R. E. Grim.
- No. 16. Attapulgite, Attapulgus, Georgia. From Paul F. Kerr, Columbia University Collection.

Fig. 5. Infrared spectrograms of minerals related structurally to clays.
- No. 22. Gibbsite, New Caledonia. Univ. of Missouri mineral collection.
- No. 21. Brucite, Wakefield, Quebec. Univ. of Missouri mineral collection.
- No. 66. Quartz, Graniteville, Missouri.
- No. 40. Hyalite opal, Guanajato, Mexico. Univ. of Missouri mineral collection.
- No. 30N. Muscovite, Jackson, No. Carolina. Univ. of Missouri mineral collection.

ECOLOGY OF MARSH AND BAY FORAMINIFERA, BARNSTABLE, MASS.

FRED B. PHLEGER AND WILLIAM R. WALTON

ABSTRACT. Fifty-five bottom samples were collected along three traverses in Barnstable Harbor, Massachusetts, and adjacent Cape Cod Bay. The Foraminifera populations are analyzed quantitatively and distribution patterns are described.

There are two principal Foraminifera facies in Barnstable Harbor and in adjacent Cape Cod Bay. Three subfacies are present in the harbor area and two subfacies occur in the Bay. Environmental conditions are described and are correlated with facies and subfacies distribution.

INTRODUCTION

THE purpose of this study is to examine Foraminifera faunas from Barnstable Harbor, Mass., and adjacent Cape Cod Bay, and to correlate the distribution with the known environmental factors.

The Barnstable Harbor area was chosen because of the great variation in environmental conditions. The harbor is small but contains all the environments characteristic of brackish water marshes (Johnson, 1925, pp. 522-528), and is adjacent to the open water of Cape Cod Bay where contrasting studies of the faunas can be made. Sandy Neck is a long sand spit between the marsh and bay environments and is the type of deposit which may be of some importance in older sedimentary rocks. It is believed that knowledge of potential micro-fossils adjacent to such a sediment may serve as a tool to point to the probable existence of a lenticular shoreline deposit in older rocks. Much work has been done on the environmental conditions existing in Barnstable Harbor by members of the Woods Hole Oceanographic Institution over a period of 2 years, and environmental conditions in this area are better known than for any other similar area along the Atlantic Coast.

No previous data are recorded on the Foraminifera of Cape Cod Bay. It is believed that the results of this study give an accurate general picture of the Foraminifera facies distribution in this part of the bay area. It is not possible to say that similar faunal facies occur elsewhere, but it is reasonable to postulate that sharp variations in the Foraminifera fauna

can be expected where similar conditions exist. It is hoped that other studies can be made in the future in order to extend knowledge of the ecology of tidal marshes and adjacent deposits.

ACKNOWLEDGMENTS

The samples were collected with the facilities of the Woods Hole Oceanographic Institution. Frances L. Parker assisted in identification of the species. The laboratory work was financed by the Office of Naval Research, under Contract N6onr-277, Task Order III. Information on ecology of the Barnstable Harbor area was furnished by J. C. Ayers of the Woods Hole Oceanographic Institution.

LOCATIONS OF SAMPLES

The area is located on the south side of Cape Cod Bay and includes approximately 100 sq. mi. Barnstable Harbor is largely a salt water marsh area separated from the open water of Cape Cod Bay by a sand spit (Sandy Neck) approximately 6 mi. long and ½ mi. wide. The harbor is connected with the bay by a tidal channel about 400 yds. wide at low water, extending the length of the harbor and varying in depth from .3 m. to 8 m.

The samples were collected during the summer of 1948 by F. B. Phleger, J. C. Ayers, and H. J. Turner. The bay samples are spaced 1 mi. apart in three traverses along the meridians 70°16′ W. Long., 70°12.7′ W. Long., and 70°21.3′ W. Long., and each traverse extends offshore for approximately 10 mi. In the harbor area the stations were spaced so that all the major environments were sampled and are in traverses which are approximate continuations of the bay traverses (fig. 1). The stations along the three traverses were spaced to obtain a representative fauna from all environments from the mainland side of the harbor, across the sand spit and into Cape Cod Bay. Traverse 3 is in the main channel of the harbor between Scorton Creek and Beach Point and continues into the bay. Locations of the stations are listed in table 1.

METHOD OF STUDY

Most of the Cape Cod Bay samples were collected with the bottom sampler constructed by Phleger. This gear obtains

a relatively undisturbed sample of the surface sediment and a short cross section extending an average of about 30 cm. beneath the surface. The upper 2 cm. of sediment from these samples was used for study of the Foraminifera. The sampler can be used only in sediment containing sufficient mud so that there is some cohesion between the particles. In sandy areas a small orange-peel dredge was used, which is modified to prevent washing of the sediments enroute to the surface of the water. Material for study was selected from the surface of each of these samples and was approximately the same amount of sediment as that selected from the short cores. Most of the samples at the very shallow stations within the harbor area were collected with a spatula.

It was considered undesirable to examine the entire sample from many stations due to the large amount of sediment in the sand samples, and only a small fraction of these was studied. Division of such samples was accomplished by means of a simple splitting device designed by Parker (1948, pp. 218-219). This apparatus consists of a small tray divided into two sections by a knife edge in the middle of a v-shaped trough inclined at approximately 45°. With this apparatus it is possible to make numerous divisions of the washed sediment and obtain a representative fraction of the entire sample. In samples where few specimens were found on first examination, the entire sample was treated with carbon tetrachloride and the residues were examined for forms not freed by flotation.

Methods used in the analysis of the data are those used by Phleger (1942) and Parker (1948). Percentages of all the species in each population were calculated. These are plotted by traverses to study variations that occur along the length of the traverses (tables 2-4). In addition, the harbor fauna percentages are plotted by ecologic zones because of the variety of existing environmental conditions (table 5).

Total population counts appearing in tables 2-5 are close approximations and are given as whole numbers. Distribution of the Foraminifera has been analyzed by plotting the faunas in two groups, the harbor fauna and the bay fauna. Each sample was classified according to general type of sediment and a brief description of the sediments is given in table 1.

THE FORAMINIFERA

THE SPECIES

Twenty-six species of Foraminifera have been identified. Some of the species are discussed briefly below and typical specimens are illustrated on plates 1 and 2. Only those species previously recorded from the North Atlantic are included in the following discussion.

Ammobaculites sp. has been assigned tentatively to the genus *Ammobaculites*. The majority of specimens lack the uniserial portion and further study is needed to reveal the internal structure of the species.

Ammobaculites cassis (Parker) varies from small and presumably young specimens to the large microspheric and megalospheric forms (plate 1). All variations occur together at most places. This species is found north from Cape Cod along the New England coast to Greenland. It is a typical sub-Arctic species and Cape Cod Bay appears to be the southernmost locality from which it has been recorded.

Armorella sphaerica Heron-Allen and Earland, a very small form which was described from the Antarctic, has been recorded from Keil Bay, Germany, and off Nonamesset Island, Mass. (Cushman, 1944). The latter is the only previously recorded occurrence from the Western Atlantic.

Eggerella advena (Cushman) is a common species in the New England region and occurs in great abundance in the Cape Cod Bay samples. It is typically a sub-Arctic species and has been found to occur abundantly in the North Atlantic.

Elphidium cf. *articulatum* (d'Orbigny) occurs only in the bay samples from water depths greater than 26 m. and is present in low percentages. It has been recorded previously only from Casco Bay, Maine (Cushman, 1944).

Elphidium incertum (Williamson) is present in both the bay and the harbor faunas but is much more abundant in the bay. It shows many variations from opaque white, thick-walled specimens to clear, almost transparent tests and has a great range in size. This species is very common along the New England coast.

Eponides frigidus (Cushman) var. *calidus* Cushman and Cole occurs in most of the bay samples. It is one of the com-

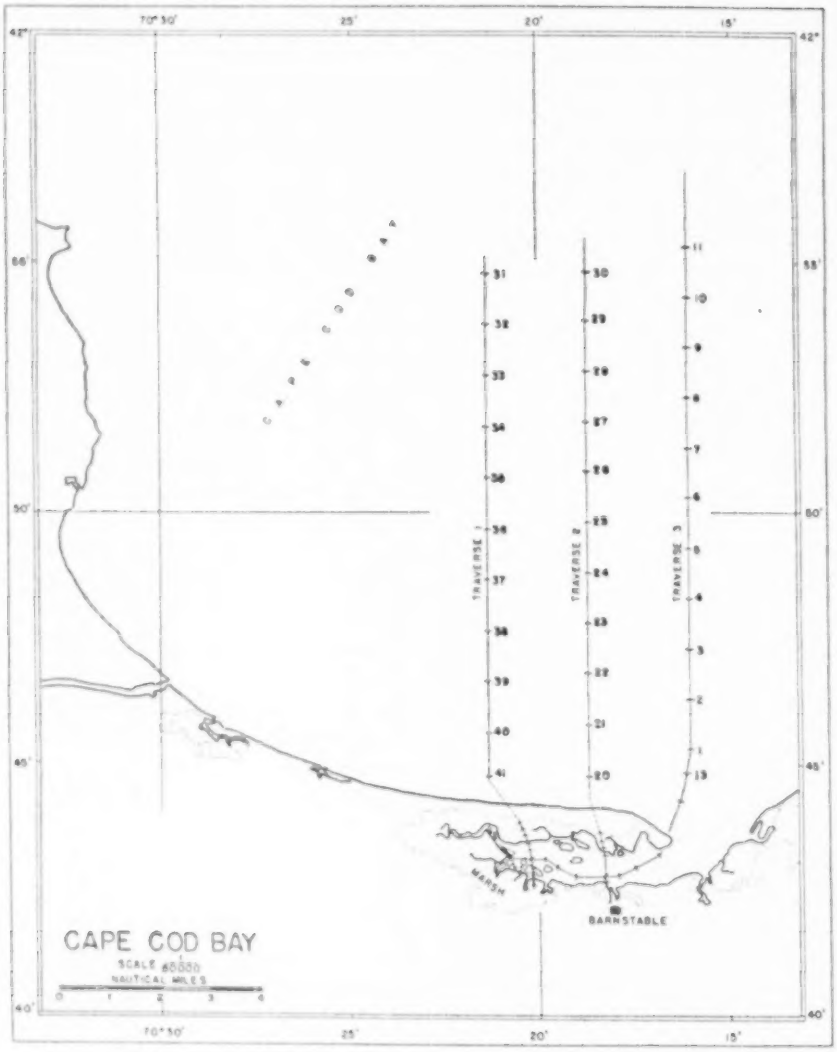


Figure 1

Chart of a portion of Cape Cod Bay showing location of traverses.

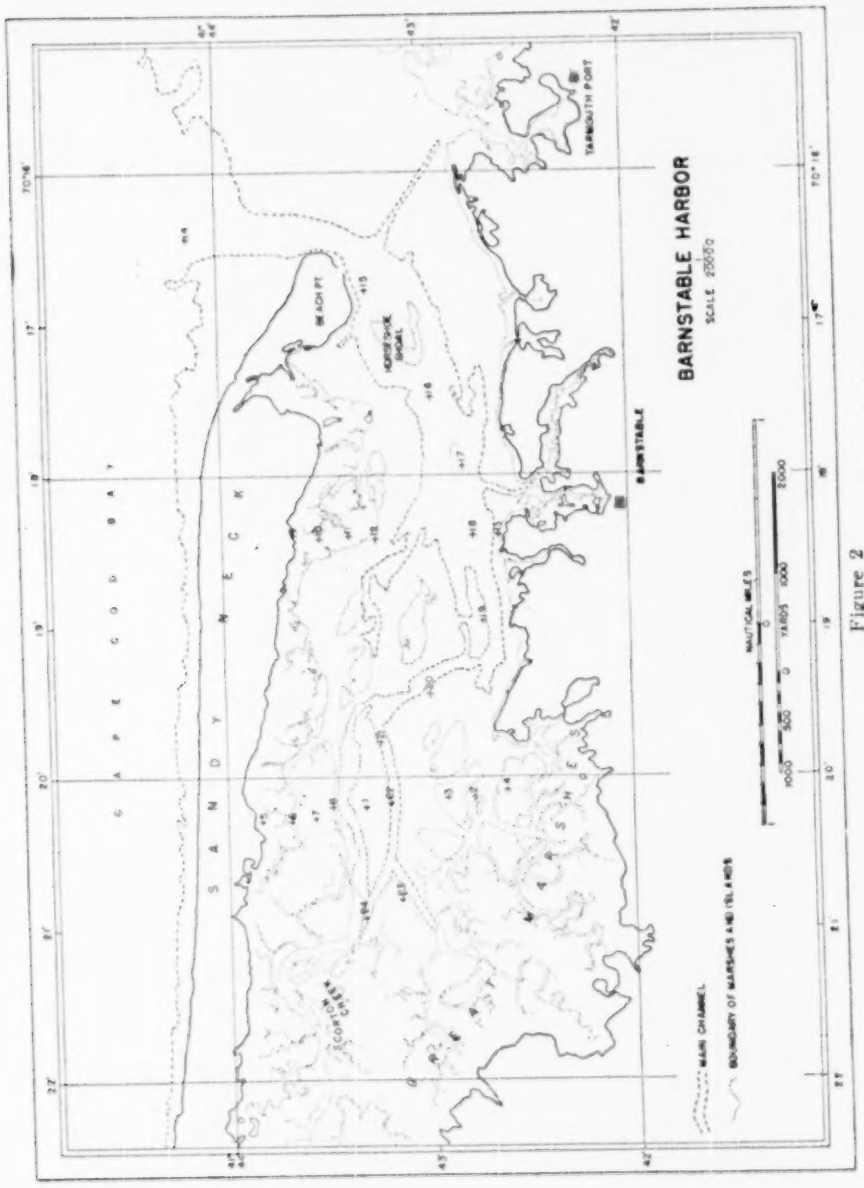


Figure 2
Barnstable Harbor chart showing locations of stations.

monest of the shallow-water forms from the New England coastal region (Cushman, 1944).

Proteonina atlantica Cushman is present in great abundance in the bay samples from the shallowest sample at 19 m. to the deepest at 38 m., 10 miles offshore. It is cool temperate to Arctic in distribution, being very common around Greenland and along the New England Coast.

Miliammina fusca (H. B. Brady) occurs almost entirely in the harbor area, but a few specimens were found in the Bay. It has been reported previously from Casco Bay, Maine (Cushman, 1944).

Reophax curtus Cushman is scattered in the bay fauna, being present in low frequency at many stations. It has been recorded previously in the vicinity of Vineyard Sound (Cushman, 1944).

Reophax cf. *arctica* H. B. Brady has been found in a few bay samples occurring with *R. curtus* and *R. scottii*.

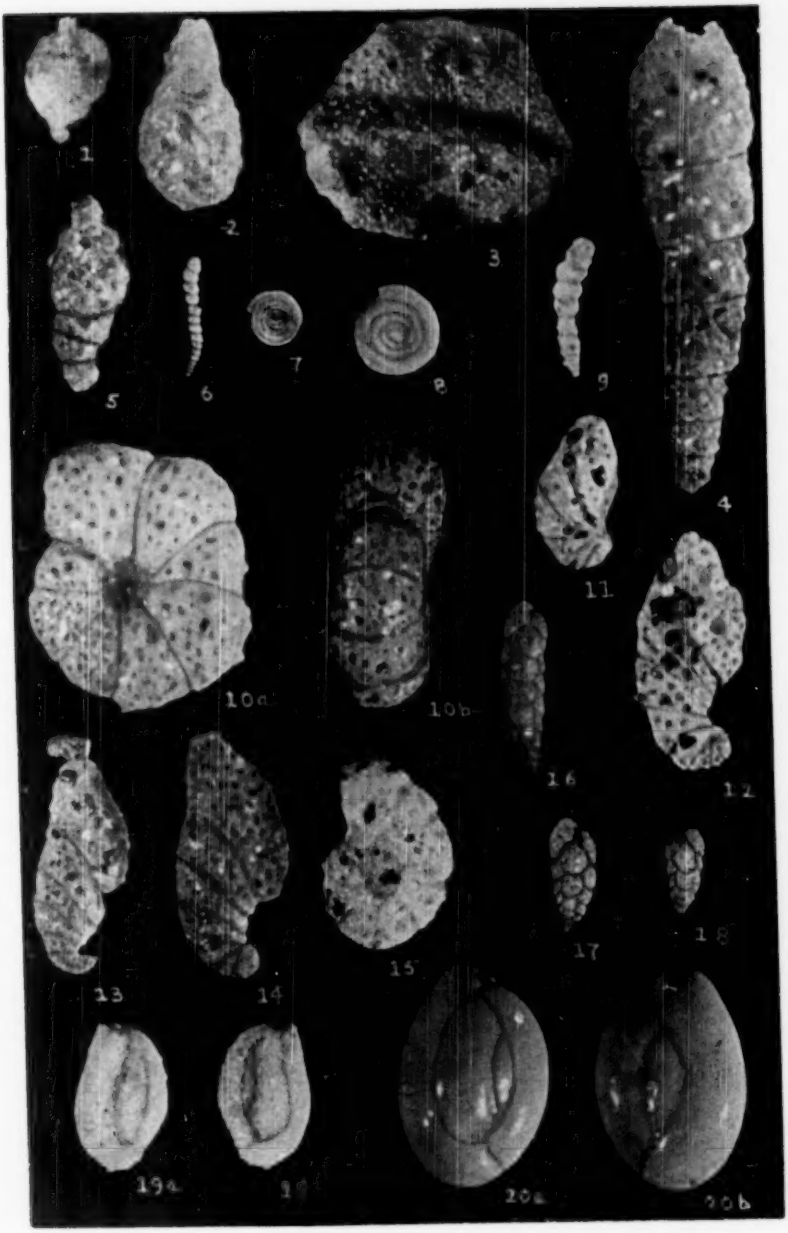
Reophax scottii Chaster occurs with *R. curtus* and is fairly abundant in many of the bay samples. It has been reported at only one other locality in the Western Atlantic, off Gay Head, Mass. (Cushman, 1944).

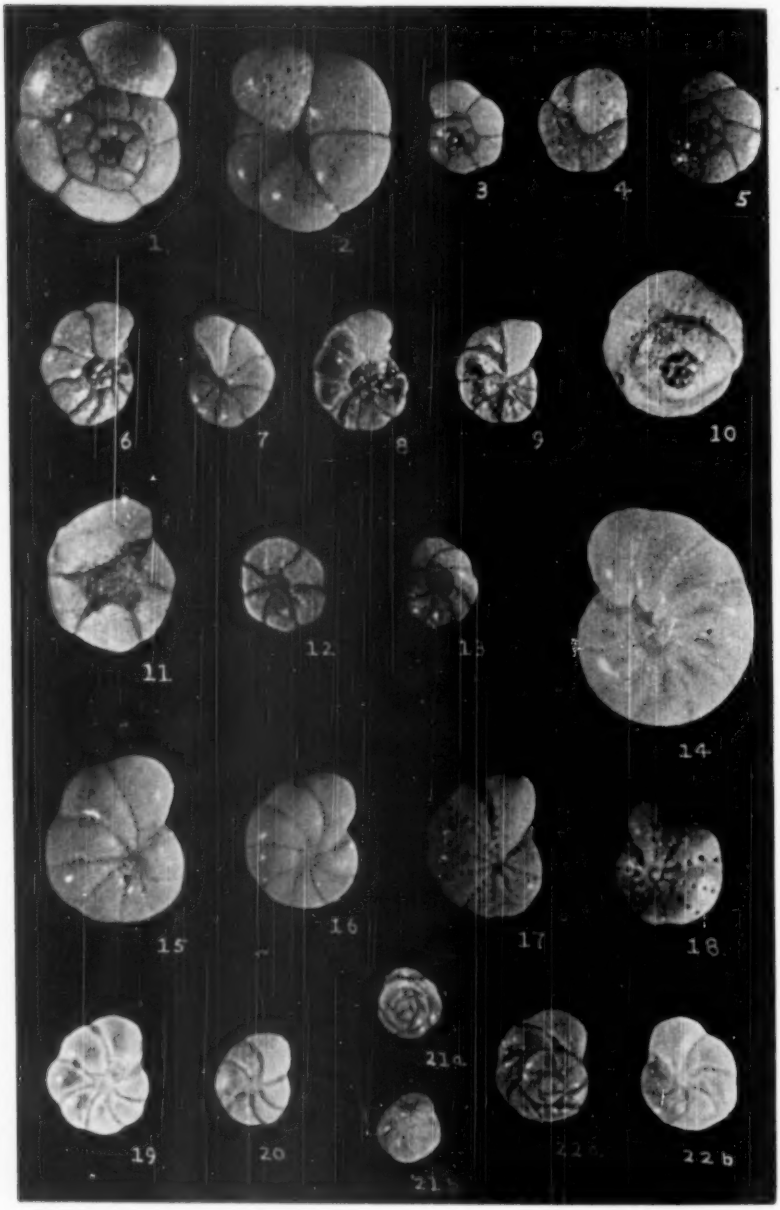
Trochammina inflata (Montagu) is present in the harbor fauna in great abundance. Specimens vary in size, but most are large and well developed. This species is common along the New England coast.

Explanation of Plate 1

Figure

1. *Arworella sphaerica* Heron-Allen and Earland. x44. Sta. H5.
2. *Proteonina atlantica* Cushman. x42. Sta. B9.
3. *Webbinella* (?) sp. x44. Sta. H5.
4. *Reophax* sp. x40. Sta. B11.
5. *Reophax curtus* Cushman. x27½. Sta. B6.
6. *Reophax scottii* Chaster. x40. Sta. B6.
7. *Ammodiscus* sp. x39. Sta. B3.
8. *Ammodiscus* sp. x42. Sta. B2.
9. *Reophax* cf. *arctica* H. B. Brady. x43. Sta. B10.
10. *Labrospira crassimargo* (Norman). x39. a) side view; b) apertural view. Sta. B9.
11-14. *Ammobaculites cassis* (Parker). 11-12) x40; 13-14) x26½. 11) Sta. B33; 12-14) Sta. B22.
15. *Ammobaculites* sp. x42. Sta. H24.
16-18. *Eggerella advena* (Cushman). 16-17) x40; 18) x44. Sta. B9.
19. *Miliammina fusca* (H. B. Brady). x42. Sta. H6.
20. *Quinqueloculina seminula* (Linne). x41. Sta. B2.


1
2
3
4
5
6
7
8
9
10a
10b
11
12
13
14
15
16
17
18
19a
19b
20a
20b


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21a
21b
22b

Trochammina lobata Cushman occurs generally throughout the harbor and the bay faunas. It is common along the New England coast and has been reported at numerous stations by Cushman (1944) and Parker (1948).

Trochammina rotaliformis J. Wright occurs with low frequency in both harbor and bay samples. It has been reported as common in Hudson Bay and at other stations along the New England coast (Cushman, 1948).

Trochammina macrescens H. B. Brady occurs in the harbor samples in about the same proportion as *T. inflata*. All variations of the chambers occur in these forms from complete deflation to the normal form. The only other recorded Atlantic occurrences are those from brackish water around the British Isles.

Trochammina squamata Parker and Jones and allied species (Höglund, 1947) have not been separated. They occur together at the same stations and are included in one count. This group occurs at most harbor and bay stations.

HARBOR FACIES

Occurrence of Foraminifera in the Barnstable Harbor samples is listed in tables 2-5. The most abundant species is *Trochammina inflata* which comprises 10 per cent to 100 per

---

Explanation of Plate 2

Figure

1-3. *Trochammina inflata* (Montagu). x43. 1-2) Sta. H6; 3) Sta. H1.

4-5. *Trochammina lobata* Cushman. x41. Sta. B3.

6-9. *Trochammina macrescens* H. B. Brady. x40. 6-7) Sta. H6; 8-9) Sta. H4.

10-11. *Trochammina rotaliformis* J. Wright. x40. Sta. H6.

12-13. *Trochammina squamata* Parker and Jones. 12) x39.; 13) x42. Sta. B9.

14-16. *Elphidium* cf. *articulatum* (d'Orbigny). 14) x43., Sta. B6; 15) x41. Sta. B6; 16) x39., Sta. B4.

17-18. *Elphidium incertum* (Williamson). 17) x41.; 18) x44. Sta. B9.

19-20. *Elphidium subarcticum* Cushman. 19) x43.; 20) x42. 19) Sta. H1; 20) Sta. H6.

21. *Eponides frigidus* (Cushman) var. *calidus* Cushman and Cole. x41. a) ventral view; b) dorsal view. Sta. B9.

22. *Valvulineria* sp. x39. a) ventral view; b) dorsal view. Sta. H6.

TABLE 1
Location of Stations

Sta.	N. Lat.	W. Long.	Depth in Meters	Sediment Description
B1	41°45.3′	70°16′	14 m.	Medium sand
B2	41°46.2′	70°16′	19 m.	Medium sand
B3	41°47.3′	70°16′	23 m.	Fine sand
B4	41°48.3′	70°16′	23 m.	Mud and sand
B5	41°49.3′	70°16′	25 m.	Mud and sand
B6	41°50.3′	70°16′	31 m.	Mud and sand
B7	41°51.3′	70°16′	32 m.	Mud and sand
B8	41°52.3′	70°16′	33 m.	Mud
B9	41°53.3′	70°16′	34 m.	Mud
B10	41°54.3′	70°16′	36 m.	Mud
B11	41°55.3′	70°16′	38 m.	Mud
B13	41°44.8′	70°16.1′	4 m.	Clean coarse sand and pebbles
B20	41°44.8′	70°18.7′	8 m.	Clean fine sand
B21	41°45.7′	70°18.7′	15 m.	Fine sand and silt
B22	41°46.8′	70°18.7′	21 m.	Fine sand and silt
B23	41°47.7′	70°18.7′	21 m.	Fine sand and silt
B24	41°48.7′	70°18.7′	26 m.	Mud and sand
B25	41°49.7′	70°18.7′	28 m.	Mud and sand
B26	41°50.7′	70°18.7′	28 m.	Mud and sand
B27	41°51.7′	70°18.7′	31 m.	Mud
B28	41°52.7′	70°18.7′	32 m.	Mud and sand
B29	41°53.7′	70°18.7′	34 m.	Mud
B30	41°54.7′	70°18.7′	38 m.	Mud
B31	41°54.7′	70°21.3′	38 m.	Mud
B32	41°53.7′	70°21.3′	36 m.	Mud
B33	41°52.7′	70°21.3′	34 m.	Mud
B34	41°51.7′	70°21.3′	32 m.	Mud
B35	41°50.7′	70°21.3′	30 m.	Fine silt and mud
B36	41°49.7′	70°21.3′	30 m.	Fine silt and mud
B37	41°48.7′	70°21.3′	28 m.	Fine silt and mud
B38	41°47.7′	70°21.3′	26 m.	Fine silt and mud
B39	41°46.7′	70°21.3′	22 m.	Fine silt and mud
B40	41°45.7′	70°21.3′	20 m.	Fine silt and mud
B41	41°44.7′	70°21.3′	12 m.	Clean fine sand
H1	41°43.4′	70°20.1′	Intertidal	Clean fine sand and shell fragments
H2	41°42.8′	70°20′	"	Coarse silt
H3	41°42.7′	70°20.1′	"	Silt
H4	41°42.5′	70°19.9′	"	Silt, high organic content
H5	41°43.9′	70°20.3′	"	Silt, high organic content
H6	41°43.7′	70°20.2′	"	Silt, high organic content
H7	41°43.6′	70°20.1′	"	Silt, high organic content
H8	41°43.5′	70°20.1′	"	Silty clay
H9	41°43.7′	70°18.4′	"	Silty clay, high organic content

TABLE 1 (Continued)

Sta.	N. Lat.	W. Long.	Depth in Meters	Sediment Description
H10	41°43.5′	70°18.4′	"	Silty clay, high organic content
H11	41°43.4′	70°18.4′	"	Silty clay, high organic content
H12	41°43.3′	70°18.4′	"	Medium clean sand
H13	41°42.6′	70°18.4′	"	Fine sand and coarse silt
H14	41°44.2′	70°16.5′	3 m.	Medium clean sand
H15	41°43.2′	70°16.8′	3 m.	Medium clean sand
H16	41°42.9′	70°17.5′	3 m.	Medium clean sand
H17	41°42.7′	70°17.9′	3 m.	Medium clean sand
H18	41°42.6′	70°18.4′	.6 m.	Medium clean sand
H19	41°42.6′	70°18.8′	.3 m.	Fine clean sand
H20	41°43.1′	70°19.5′	.3 m.	Fine clean sand
H21	41°43.3′	70°19.7′	.3 m.	Fine clean sand
H22	41°43.3′	70°20.2′	.3 m.	Coarse silt and fine sand
H23	41°43.4′	70°21′	.3 m.	Clean fine sand
H24	41°43.4′	70°21′	.3 m.	Clean fine sand

cent of the fauna in each harbor sample, except those which were taken from the channel. Next in abundance is *T. macrescens* which also is a large percentage of the fauna. *T. rotaliformis* is not abundant and occurs both in the harbor and bay faunas (see tables 2-4). *Armorella sphaerica* and *Webbinella* (?) sp. are all restricted to the harbor but make up a very small per cent of the samples in which they occur. *Ammobaculites* sp. occurs only in the harbor and although restricted in distribution is a significant percentage of the fauna in the samples where it occurs (see H3, H22, H21, tables 2, 4).

Trochammina lobata and *Trochammina squamata* and varieties occur in fairly high percentages throughout both the harbor and bay faunas (table 2). *Elphidium incertum* and *Elphidium subarcticum* both are present in the harbor but are much more abundant in the bay (table 2).

There are four major zones in the harbor area based on floral distribution; the *Spartina patens* zone, in which those forms live that will endure wetting by tidal action for only a brief period, the *Spartina glabra* zone, in which those forms live that require daily submergence by the tides, the intertidal zone or "mud flat" zone, and the *Zostera* zone (eel grass zone), which is continually submerged (Johnson, 1925). In Barnstable Harbor parts of the *Zostera* zone are exposed at low tide.

The greatest total populations of harbor Foraminifera occur in the high marsh (*Spartina patens* and *Spartina glabra* zones). The fauna is composed principally of *Trochammina inflata* and *T. macrescens* from stations H3, H4, H5, H6, H7, H10, and H11. *Armorella sphaerica*, *Webbinella* (?) sp.

| TRAVERSE 1 | | |

and *Valvulineria* sp. are confined to these zones, and the greatest frequency of *Miliammina fusca* occurs in the high marsh (table 5). The total amount of organic material in the sediments also is much greater here. Apparently anomalous faunas occur at stations H2 and H9. Station H2 is located on a small sandy island in the *Spartina glabra* zone, but the total population is small and only two species are found. Sample H9,

TRAVERSE 2																				
STATION	H13	H18	H12	H11	H10	H9	B20	B21	B22	B23	B24	B25	B26	B27	B28	B29	B30			
DEPTH IN METERS							8	15	20	21	26	28	28	31	32	34	38			
TOTAL BENTHONIC POPULATION	32	8	23	6600	1100	4	4	2	900	1100	9600	1200	1500	1400	1500	1800	700			
BENTHONIC SPECIES IN %																				
AMMOBACULITES CASSIS									7		4	1	6	9	2	3	2			
AMMODISCUS SP.									3	3	.5									
ARMORELLA SPHAERICA					2												1			
EGGERELLA ADVENA							75		14	18	8	54	32	26	25	32	37			
ELPHIDIUM ARTICULATUM											1		4				3			
E. INCERTUM	53		22								5	8	4	2	4	3	26			
E. INCERTUM VAR. CLAVATUM											.5		2				3			
E. SUBARCTICUM			26						3		1				2	3	1			
EPONIDES FRIGIDUS VAR. CALIDUS									3		.2		4		2	.9	1			
GLOMOSPIRA CF. GORDIALIS										3			2		2					
LABROSPIRA CRASSIMARGO														1			1			
PROTEONINA ATLANTICA									52	67	55	24	26	49	54	41	14			
MILIAMMINA FUSCA	13		17	41							3									
Q. SEMINULA											.3					.9				
REOPHAX CURTUS											2	4	4	1						
R. SCOTTII											.3	1	11	8	2	6	8			
R. SCORPIURUS																4				
SPIROPLECTAMMINA BIFORMIS													2	2	2	.9				
TROCHAMMINA INFLATA	22		30	37	23	100														
T. LOBATA				2	7			100	14	9	22	3				.9				
T. MACRESCENS	13			20	30															
T. CF. ROTALIFORMIS				.5	30		25		3			1								
T. SQUAMATA		100	4								.5	3	2	1	4	6	5			
WEBBINELLA (?) SP.					10															

TABLE 8

Percentage Distribution of Foraminifera in Traverse 2

taken at the junction of the marsh zone and the sand dunes of Sandy Neck, contains four specimens of *Trochammina inflata*.

Total populations are much smaller in the intertidal flat zone than in the high marsh at stations H1, H8, H12, and

| TRAVERSE 3 | | |

BARNSTABLE HARBOR STATIONS

	ZOSTERA AND BELOW ZOSTERA ZONES											MUD FLAT ZONE				SPARTINA PATENS AND SPARTINA GLABRA ZONES									
STATION	14	15	16	17	18	19	20	21	22	23	24	1	8	12	13	2	3	4	5	6	7	9	10	11
TOTAL BENTHONIC POPULATION	2	1	54	18	8	—	—	100	500	100	50	700	1700	20	30	100	1100	6700	8900	9300	9600	4	1150	6700
BENTHONIC SPECIES IN %																								
AMMOBACULITES SP.								15	33	1	5	19					42							
AMMODISCUS SP.										1														
ARMORELLA SPHAERICA																				2	2		2	
EGGERELLA ADVENA				17						1	7					67				.1				
ELPHIDIUM INCERTUM				11										22	53					.3				
E. SUBARCTICUM				11						1	7	.7		26						.1				
LABROSPIRA CRASSIMARGO									3															
MILIAMMINA FUSCA										44	9	.1		17	13		6		2	25	9			41
TROCHAMMINA INFLATA		100		11				72	43	43	61	46	90	30	22	33	40	26	39	12	10	100	23	37
T. LOBATA				6				15	3	6	7	7	8				1		5	9	2		7	2
T. MACRESCENS				6					14	3	2	25	3		13		6	74	45	33	67		30	20
T. CF. ROTALIFORMIS									3										3	4	1		30	.5
T. SQUAMATA	100		100	39	100						2	3		4			4							
WEBBINELLA (?) SP.																		.2	5	8	5		10	
VALVULINERIA SP.																		.3		4	4			

TABLE 5

Percentage Distribution of Harbor Foraminifera arranged According to Ecologic Zones

H13. Stations H12 and H13 appear to contain the only characteristic intertidal flat fauna. The presence of *Elphidium incertum* makes this zone distinctive. Apparent faunal anomalies in this zone exist at stations H1 and H8. Stations H1 and H8 have relatively high total populations although located in the intertidal flat zone which generally is characterized by small populations.

The channel stations (*Zostera* zone or below *Zostera* zone), H14, H15, H16, H17, H18, H19, H20, H21, H22, H23, and H24, are always submerged. The Foraminifera populations of the channels are small but generally contain the same species as the other zones, with the exception of stations H21, H22, H23, and H24 which have the greatest total populations of the channel stations, and correspond more closely to the fauna of the intertidal flat and high marsh areas in having numerous specimens of *Trochammina inflata* and *T. macrescens* (table 5).

BAY FACIES

The bay fauna is characterized by *Proteonina atlantica* and *Eggerella advena* which make up approximately 90 per cent of the Foraminifera populations. *Proteonina atlantica* is somewhat more abundant than *Eggerella advena*, but both species occur in most bay samples. *Ammobaculites cassis* is fairly abundant and is restricted to the bay. The following species are restricted to the bay but constitute a relatively small percentage of the samples in which they occur: *Ammodiscus* sp., *Elphidium articulatum*, *Eponides frigidus* var. *calidus*, *Glomospira* cf. *gordialis* and *Quinqueloculina seminula*. *Reophax* is restricted to the bay and the various species usually occur in the sand samples.

There are two subfacies in the bay fauna which are characterized by different species and different frequencies of species. The nearshore facies is developed on the sandy bottom which is present at depths shallower than approximately 20 m. It is characterized by *Eggerella advena* and *Proteonina atlantica* which compose most of the Foraminifera population although 3 or 4 other species may occur in low abundance in any sample.

A second bay subfacies is present from approximately 20 to 30 m. water depth to the outer end of the traverses; this is the area which has a mud and sand or mud bottom. The

following species appear to be restricted to the mud and sand or mud subfacies:

Ammodiscus sp.
Ammobaculites cassis
Elphidium articulatum
Eponides frigidus var. *calidus*
Glomospira cf. *gordialis*
Quinqueloculina seminula
Reophax scorpiurus
R. scottii
R. curtus

The following species generally have their highest frequencies in the mud and sand and mud subfacies:

Elphidium incertum
E. incertum var. *clavatum*
E. subarcticum
Trochammina squamata

Some faunal mixing is apparent in the samples from traverse 3, especially between the harbor facies and the sand subfacies of the bay. This probably is due to strong tidal currents localized near the entrance of the harbor.

DISCUSSION

Currents in Barnstable Harbor are controlled almost exclusively by the tides. There is very little fresh water drainage into the harbor. The physiography of the harbor is such that the tide is asymetrical, there being 7 hours of ebb and 5 hours of flood. Intertidal flats within the harbor are little affected by the strong currents of late ebb, for they become exposed before the time of maximum ebb currents. The small populations of Foraminifera from the channel stations undoubtedly are to be correlated with tidal scour.

The intertidal flats (stations H1, H8, H12, and H13) are not affected by the strong currents of late ebb but do shift with other stages of the tide and are practically barren of vegetation. Lack of protective vegetation and the coarseness of the shifting sand of the intertidal flats probably are not conducive to a large Foraminifera population (table 5).

The largest Foraminifera populations in the harbor area occur in the "high marsh" (*Spartina patens* and *Spartina*

glabra zones combined). There are two possible explanations for these large populations: either environmental conditions in the high marsh will support an abundant Foraminifera fauna, or specimens are washed there by the tidal currents. The high marsh areas are covered by a matted growth of marsh grasses and are completely submerged by only the highest spring tides or by occasional wind-driven tides. These areas usually are wetted from underneath twice daily at high tide. There is a high production of a variety of organisms and organic material accumulates in abundance. These areas offer good protection for Foraminifera because of the absence of strong currents and possible nectonic predators. Very little movement occurs that would tend to crush or destroy fragile tests. The tides which submerge the high marsh carry with them considerable detritus which may include Foraminifera. These grass areas are excellent settling ground for any material which is suspended in the water, as shown by Shaler (1886). The tough stemmed grasses have a dampening effect on any incoming currents and much of the suspended material settles out.

It is probable that the high populations of Foraminifera are not washed in by highest tide but reproduce and grow in the high marsh. The forms found are very well developed, and few broken shells are found as may be expected if most of them are transported by currents for any distance. It seems improbable that so few inundations of the high marshes would account for such concentrated populations if they were transported and deposited in that environment. The restriction of 3 species to this habitat strongly suggests that it is an indigenous fauna.

It is interesting to note the contrast between total populations at the stations of traverses 1 and 2 in the marsh area; the largest total populations occur in traverse 1. The position of traverse 1 can be correlated approximately with the extreme limit of the Cape Cod Bay water as it enters the harbor on the incoming tide. It is at this line that the mass of bay water has its lowest velocity during late flood tide and the line where the greatest amount of settling of suspended material occurs.

Stations H1, H2, H3, H8, and H9 have faunas apparently anomalous for their subfacies. Station H1 is in an intertidal

flat close to the channel and its population is similar to the fauna of channel stations. The intertidal flats shift continuously, as do the channels, and it is not unexpected to find faunal mixing. Similar conditions exist at stations H2 and H3 in the *Spartina glabra* zone. These stations are located on sandy islands subject to changes by tidal current action and surrounded by channels, and small total populations are expected. Station H8, although in the intertidal flat zone, has a relatively high total population. It is located at the boundary between the marsh and an intertidal flat and its population is very similar to that of the high marsh areas. Station H9 was taken at the boundary between the high marsh and the dunes of Sandy Neck. This area is above water except during extremely high tides and it is in an area where there is subsurface fresh water seepage from the sand dunes; a small total population may be expected under such conditions.

Sediments at the channel stations are fine sand to coarse sand and contain little organic material. The sediments are related to strong currents along the channels during late ebb tide. Sediments of the intertidal flats are sand and silt with shell fragments and contain little organic material. The broken shells appear to be a result of the shifting sand of the intertidal flats crushing shells deposited there by flood tides. The sediments of the high marsh areas are composed of fine silt and rather coarse sand and have a high organic content. These sediments are composed of wind-blown sand from the dunes and fine silt washed up by tidal action and settled out of the water as indicated above. On a windy day the amount of wind-blown sand being deposited in these marsh areas is quite noticeable.

Salinity variations are not as great as would be expected in the harbor area. When the high marsh is covered by highest tides the water has a salinity range of 31.5°/00 to 32°/00. Under normal tidal conditions, however, these areas are wetted from underneath by water with the same salinity range as that of the intertidal flat zones, 25°/00 to 31°/00. These are maximum and minimum ranges and under normal tidal conditions the salinity range is approximately 28°/00 to 31°/00 on the intertidal flats. The channel stations at the head of the harbor (H22, H23, and H24) show the greatest salinity variation ranging from 20°/00 after a period of heavy pre-

cipitation and on the ebb tide to 31.5°/00 under normal conditions. Stations H14 and H15 at the mouth of the Harbor have salinity ranges of 31°/00 to 32°/00. The rest of the channel stations, H16, H17, H18, H19, H20, H21, all have about the same salinity range of 27.5°/00 to 31.5°/00.

Considerable work has been done on the productivity of the water of Barnstable Harbor by J. C. Ayers (personal communication). It has been found that the carbon content of the water varies from .0-.1 mgms./liter at the mouth of the harbor to .1-1 mgms./liter at the head of the harbor. This can be correlated with areas of greatest total Foraminifera populations which occur in traverse 1 in the harbor in the area where the water has the highest organic production.

The water temperatures of Barnstable Harbor are characterized as follows by J. C. Ayers (personal communication):

"Like most estuaries Barnstable Harbor warms the tidal water which enters it during the spring and summer and cools the entering tidal water during the fall and winter. Transition periods between warming and cooling occur twice a year, generally in March-April and in September-October. During these periods there is no horizontal temperature gradient along the length of the harbor. During the spring and summer there is a temperature difference between the head of the harbor and the harbor mouth of about 10°F. The incoming water at each point averages around 70°F., while the water at the head of the harbor averages about 80°F. These figures are for low tide when the greatest temperature differences occur. During the fall and winter the gradient from mouth to harbor head is about 5°F. At low tide in these seasons water in the head of the harbor is about 35°F. while at Beach Point, about 40°F."

The two Foraminifera subfacies of the bay areas can be correlated with the mud line. The nearshore sediments are composed of fine to coarse clean sand in water shallower than approximately 20 m. At approximately 20 m. the sediments become silty and grade into mud and sand, or mud, which continues offshore to a water depth of approximately 32 m. The greatest number of species and the largest populations occur in the deeper facies. The distribution of the Foraminifera from all stations deeper than 20 m. is fairly constant.

The salinity of the bay water is approximately 31°/00 to 32°/00 and remains fairly constant. The temperature cycle of Cape Cod Bay water is typical for nearshore water in cool temperate latitudes. Temperature data on the bay water in this area have been taken from the files of the Woods Hole Oceanographic Institution and are listed below. Temperatures are given in degrees Fahrenheit.

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Om.	32.5	34.1	35.9	42.6	50.5	59.4	65.5	64.9	64.0	55.3	48.8	42.3
15 m.	——	34.9	34.9	42.3	45.9	54.9	——	58.7	58.0	55.1	48.8	42.3

It is quite apparent that temperature is relatively unimportant as an ecological factor affecting the distribution of Foraminifera within this part of Cape Cod Bay except that all the populations are of a cool temperate type. The maximum summer water temperature within Barnstable Harbor is higher than in Cape Cod Bay; this may be an ecologic factor of importance in causing differences in the Foraminifera facies of the harbor and the bay areas. Minimum salinity ranges within the harbor are an additional ecological factor which probably influences the differences between harbor and bay facies. In the Barnstable Harbor area the subfacies mainly are to be correlated with effects of tidal action or movement of bottom materials, degree of wetting provided, and organic production. Subfacies within the bay are to be correlated with the type of bottom material and thus the intensity of current and wave agitation of the bottom.

The desirability of more detailed study in this area is evident. It is important to obtain data on distribution of living Foraminifera to determine how much mixing of faunas is caused by tidal currents. There are numerous salt water marshes along the shoreline of Cape Cod and the adjacent New England coast which have environmental conditions similar to those of Barnstable Harbor. It is suggested that detailed studies be made of some of these marshes, analyzing surface distribution of Foraminifera faunas and also their vertical distribution in cores taken from the marshes. It is probable that similar faunal facies will be found in marshes in the New England region and elsewhere. It should be possible to reconstruct the detailed history of an old marsh area on the basis of Foraminifera.

CONCLUSIONS

(1) Barnstable Harbor contains a Foraminifera facies characterized by abundance of *Trochammina inflata* and related species. This is distinct from the adjacent nearshore Cape Cod facies which is characterized by *Proteonina atlantica* and *Eggerella advena*. Temperature and salinity differences are important ecologic factors in this distribution.

(2) There are at least 3 subfacies in Barnstable Harbor, developed on the high marsh, the intertidal flats, and in the channels. Distribution of these subfacies appears related to diurnal tidal action, nature and movement of bottom materials, presence of marsh grass and relative organic production.

(3) In Cape Cod Bay there is a nearshore Foraminifera subfacies, developed on sand bottom. A subfacies occurs offshore from the sand area which is in mud and sand or mud and is especially characterized by species of *Reophax*.

(4) The largest Foraminifera population occurs in Barnstable Harbor in the high marsh where there is the highest total organic production.

REFERENCES

Cushman, J. A., 1940. Foraminifera: their classification and economic use, 3rd ed., Harvard University Press.

———, 1944. Foraminifera from the shallow water of the New England coast: Cushman Lab. for Foram. Research, Special Publ. No. 12.

———, 1948. Arctic Foraminifera: Cushman Lab. for Foram. Research, Special Publ. No. 23, 79 pp.

Höglund, H., 1947. Foraminifera in the Gullmar Fjord and the Skagerak: Zool. Bidr. Fran Uppsala, Bd. 26, pp. 203-212, pls. 15-16.

Johnson, Douglas W., 1925. The New England-Acadian shoreline, New York, John Wiley & Sons, Inc., pp. 522-528.

Parker, F. L., 1948. Foraminifera of the continental shelf from the Gulf of Maine to Maryland: Harvard College Mus. Comp. Zool. Bull., vol. 100, no. 2, pp. 214-241.

Phleger, F. B., Jr., 1942. Foraminifera of submarine cores from the continental slope, part 2: Geol. Soc. America Bull., vol. 53, pp. 1073-1098.

Shaler, N. S., 1886. Preliminary report on sea-coast swamps of the Eastern United States: Extract from 6th Ann. Rept. of the Director, 1884-85, U. S. Geol. Survey.

CONTRIBUTION NO. 3, MARINE FORAMINIFERA LABORATORY

CONTRIBUTION NO. 507, WOODS HOLE OCEANOGRAPHIC INSTITUTION

REVIEW

The Meaning of Evolution; by GEORGE GAYLORD SIMPSON. Pp. xv, 364; 38 text figs. New Haven, 1949 (Yale University Press, $3.75).—This penetrating analysis of the course of organic evolution and of the causes underlying it, followed by an attempt to find therein some basis for human ethics and morality, is an amplification of the Terry Lectures delivered at Yale University in 1948. Accepting the factual truth of evolution as well established, Dr. Simpson presents a condensed yet comprehensive outline of the known history of life and a new analysis of its underlying principles. Aside from a tendency toward increase in the total amount of living matter, the course of evolution seems largely random and opportunistic. Oriented segments of evolutionary lines provide a crucial test for materialistic, vitalistic, and finalistic theories of the cause of evolution. Adaptation, which has a known mechanism in the action of natural selection upon the genetics of populations, is found to be the orienting factor in all real trends; hereditary changes have no direct relationship to the needs of animals or their opportunities for evolution; they provide an explanation for the randomness of evolution whereas natural selection resulting in adaptation is the orienting force. Non-adaptive changes are possible and may lead to the formation of higher systematic groups; such evolution is likely to be more rapid than normal, but is still the result of the same forces. Progress is not a universal feature of evolution; many criteria of progress are possible and each of them gives a branching pattern rather than a single line succession of types. By most but not all criteria man stands at the top of the animal kingdom. The history of life is flatly inconsistent with vitalism and finalism.

Man is a unique animal which has added a new type of evolution, based on the transmission and inheritance of learning, to the older organic evolution. This new evolution follows different laws and is subject to conscious control. However man and his unique attributes have arisen entirely through the materialistic operation of organic evolution. Man is not the goal of evolution, which was not planned.

Intuitive and naturalistic attempts to discover an absolute ethic have failed because ethics are relative and arose only with man. An ethic cannot automatically arise from the principles of organic evolution, but must be the result of rational choice. Knowledge and its transmission are the most basic features of the new, human evolution; promotion of knowledge is held to be good, for mankind, and is taken as a basic ethical proposition. The possession of knowledge and power of choice by man entail responsibility, and

the highest and most essential moral standards are involved in the fact of man's personal responsibility. Ethics based on these propositions are applied to a variety of human situations.

Evolution will continue. Man may bring about his own extinction, but he has the power to guide his own evolution and also that of other organisms. So long as human beings exist, there is no danger of a comparable animal arising to compete with them. Guidance of social evolution involves choice of ethical standards; the choice can be such that the evolution of mankind will be upward.

The agreeable ethical conclusions which Dr. Simpson derives from his study of evolution seem better grounded than earlier attempts along this line. One may suspect that his attack on the notions of a "struggle for existence" as an important part of the selection mechanism was influenced by a desire to eliminate the "tooth and claw" ethic which has been drawn therefrom; yet by his own premises that pre-human evolution was amoral and that ethics must apply specifically to mankind, such an ethic can be eliminated and the mechanism of selection has no bearing on the ethic of knowledge which he develops. Natural Selection, as Simpson says, is a matter of differential reproduction, but it seems to the reviewer that the success of each individual in coping with its environment for survival up to the time of reproduction—which is the essence of Darwin's statement—is a major determinant of which shall be able to reproduce.

The work as a whole is extremely readable, smooth in style, and with a minimum of technical jargon. It is legibly printed for the most part, but some charts have been reduced too much for clarity. The chart of the reptilian Orders has the Cenozoic Era spread out to greater length than the much longer time from Pennsylvanian to Cretaceous, which gives an illusion of excessive longevity to the survivors of the Mesozoic reptilian radiation. Full appreciation of the interpretive chapters in the second section of the book requires a greater knowledge of biology than the outline presented affords, but the central arguments can be followed by any educated reader. Results of recent advances in evolutionary theory are brought together in more condensed form, and frequently are more clearly stated than they have been hitherto; for this reason alone the book should be of value to every biologist.

JOSEPH T. GREGORY

AMERICAN JOURNAL OF SCIENCE

Established in 1818 by Benjamin Silliman

THE FIRST SCIENTIFIC JOURNAL IN THE UNITED STATES

DEVOTED TO THE GEOLOGICAL SCIENCES AND TO RELATED FIELDS

Editor: CHESTER RAY LONGWELL
Assistant Editor: JOHN RODGERS

Published monthly, one volume annually

The JOURNAL completed its *first* series of 50 volumes in 1845, its *second* series of 50 volumes in 1870, its *third* series of 50 volumes in 1895, its *fourth* series of 50 volumes in 1920, its *fifth* series of 36 volumes in 1938. Since 1938 the numbering by series has been discontinued, and the volumes bear the whole numbers as of 1818, that of 1939 being volume 237.

Back numbers and volumes, also cumulative indices of all series, may with few exceptions be obtained from the office of the AMERICAN JOURNAL OF SCIENCE, 501 Sterling Tower, New Haven, Conn.

INSTRUCTIONS TO CONTRIBUTORS

Manuscripts of articles submitted should follow the recommendations in the pamphlet "Suggestions to Authors" (Lane, 1935) and should be preceded by brief abstracts. They should be checked with special care before being submitted, to avoid changes in proof other than printer's errors.

References to literature should be listed alphabetically by authors at the end of the article, as at the foot of this page. All references should be *complete* and should comprise in order: Author's name, year of publication, Full title; name of periodical or series, volume number, inclusive pages, place of publication (if needed to identify book or periodical). Except that the year should follow the author's name directly, references should follow the form given in "Suggestions to Authors" (Lane, 1935, pp. 16-29). Within the article, the citation should be to author and year, and to specific pages if appropriate; for example: (Stearns, 1945b, fig. 2, p. 617).

Plates (photographs), *figures* (line drawings), and *footnotes* should each be numbered consecutively through each article, using arabic numerals. If two photographs form one plate, they will be figures 1 and 2 of that plate.

The *preparation* of illustrations is particularly important. Copy that cannot be reproduced cannot be accepted. Plates and figures should be capable of reduction to not more than 4 by 7 inches, all lettering being at least 1/16 in. high after reduction. When necessary, one large map or table can be accepted, if it will not exceed 7 inches in one dimension after reduction. Line drawings should be in black India ink on white drawing board, tracing cloth, or coördinate paper printed in blue. Photographs should be glossy, positive prints. Photostatic and typewritten material cannot be accepted as copy for illustrations.

Reprints. Thirty separate copies of each article will be furnished to the author free of cost and without previous notice from him; these will be without a cover and will show reference to volume, page, and year. Additional copies will be furnished at cost, which will of course be greater if the article is accompanied by plates involving unusual expense. Copies will be furnished with a printed cover giving the title, etc., when specially ordered.

Subscription rate $8 per year (75 cents a number). Student rate $5 per year (application blanks available on request). Postage prepaid to the United States and Central and South America; 35 cents a year to Canada; 60 cents a year elsewhere.

REFERENCES

Lane, B. H., 1935. Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, 25¢.)

Stearns, H. T., 1945a. Glaciation of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 56, pp. 267-274.

———, 1945b. Late Geologic history of the Pacific basin: AM. JOUR. SCI., vol. 243, pp. 614-626.

Entered as second-class matter at the Post Office at New Haven, Conn., under the Act of March 8, 1879.

VOL. 248 No. 4, 1950

CONTENTS

THE JADEITE PROBLEM. PART I ..... *Hatten S. Yoder, Jr.* 225

STRATIGRAPHIC STUDIES IN NORTHERN PERU
Bernhard Kummel 249

THE ABSORPTION OF INFRARED RADIATION BY CLAY MINERALS
W. D. Keller and E. E. Pickett 264

ECOLOGY OF MARSH AND BAY FORAMINIFERA, BARNSTABLE, MASS. ..... *Fred B. Phleger and William R. Walton* 274

REVIEW

The Meaning of Evolution; by GEORGE GAYLORD SIMPSON .. *Joseph T. Gregory* 293

PAYNE & LANE, *Printers* — NEW HAVEN, CONN.